

---

# Mars Science Laboratory

## Extended Kalman Filter (EKF)

### Technology Test Report

---

Document Number: TBD  
(JPL D-TBD)  
Revision: Draft  
Date: May 7, 2003

**Prepared by:**  
Terry Huntsberger

**Testing Team:**  
Terry Huntsberger  
Hrand Aghazarian  
Mike Garrett  
Lee Magnone

**CLARAty Support:**  
Dan Gaines

*Paper copies of this document may not be current and should not be relied on for official purposes. The current version is in the MSL Project Library at <http://mars07-lib.jpl.nasa.gov>, in the TBD folder.*



Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, CA 91109-8099

**Signature Sheet**

Approval:

---

Terry Huntsberger, Task Manager

---

Richard Volpe, Mars Technology Program Office

---

Sandy Krasner,

---

**Revision History**

<b>Revision</b>	<b>Date</b>	<b>Description</b>
Draft	05/14/2003	First Draft

**Auxiliary Documents**

<b>Document</b>	<b>Date</b>	<b>Source</b>
EKF FDD	02/01/2003	Document # TBD
EKF Test Plan	02/06/2003	Document # TBD
EKF Test Procedure	04/01/2003	Document # TBD

## Table of Contents

Executive Summary .....	5
Format for Test Results .....	9
4.1.2 Rover Baseline Tests .....	10
Test1: Drive 1 m .....	10
Test2: Drive -1 m .....	12
Test3: Turn-in-Place 30° .....	13
Test4: Turn-in-Place -60° .....	14
Test5: Drive Arc 1 m, 45° .....	15
Test6: Drive Arc 1m , -45° .....	16
4.1.3 EKF No Motion Test .....	17
Test1: Heading 0° .....	17
Test2: Heading 90° .....	17
Test3: Heading 180° .....	18
Test4: Heading 270° .....	18
4.1.4 Odometry Tests .....	19
Test1: Drive 1 m .....	19
Test2: Drive 3 m .....	20
Test3: Drive -1 m .....	21
Test4: Drive -3 m .....	22
Test5: Drive Arc 1 m, 45° .....	23
Test 6: Drive Arc 2 m, 45° .....	24
Test7: Drive Arc 1 m, -45° .....	25
Test8: Drive Arc 2 m, -45° .....	26
Test9: Turn-in-place 45° .....	27
Test10: Turn-in-place -45° .....	28
Test11: Turn-in-place 45° and then 320° .....	29
Test12: Turn-in-place -45° and then -320° .....	30
Test13: Drive 1.50 m with standard obstacle on right side (0.6 m from center) .....	31
Test14: Drive 3 m with standard obstacle on right side (0.6 m from center) .....	32
Test15: Drive Arc 3 m, 45° with standard obstacle on right side (0.6 m from center) .....	33
Test16: Turn-in-place 180° with standard obstacle in center of front wheels .....	34
Test17: Turn-in-place 5° .....	35
Test18: Turn-in-place -5° .....	36
4.1.5 EKF Turn-in-place Tests .....	37
Test1: Turn-in-place 45° .....	37
Test2: Turn-in-place -45° .....	38
Test3: Turn-in-place 180° with Standard obstacle in between front wheels .....	39
Test4: Turn-in-place 5° .....	40
Test5: Turn-in-place -5° .....	41
4-1-6 EKF Sequential Path Drive Tests .....	42
Test1: Zig-Zag Drive .....	42
Test 2: Square Drive .....	44
Test 3: S-Arc Drive .....	46
Summary Charts.....	48

## Executive Summary

The testing and validation of the extended Kalman filter (EKF) technology algorithm derived from the FIDO implementation was conducted from March 3 to April 8, 2003 on the Rocky8 rover under the CLARAty system in the MarsYard at JPL. All tests were run in a relatively benign area of the MarsYard (NW quadrant). A series of 31 tests were run to test the algorithm for localization accuracy during straight-line and arc drives, turns-in-place, drives and turns with obstacles, and drives/turns that simulate obstacle avoidance. The original test plan was designed to test the individual components of the EKF algorithm in isolation and finally in coordination. The test procedure was modified due to the inability of the current testing interface to disable the EKF while data logging. This will be addressed in future implementations of the testing interface.

The tests that were run are detailed in the Test Matrix below and were performed to test the behavior of the EKF algorithm with respect to the current MSL reference mission baseline of a localization error of 3% of the total distance traveled. Localization errors for long distance traverse can also be traced to errors in heading due to slip during turns-in-place, so a portion of the test evaluated the uncorrected heading errors. All results were compared to ground truth data that was collected by a Leica TCRA1103+ TotalStation (rated accuracy of 2mm at 10m range). The test setup is shown in Figure 1, where the Rocky8 rover has four fiducial markers (one on each corner of the rover) that are used for ranging each time before and after the tests. This setup allows us to extract both position and heading information. The test setups for the driving over a standard obstacle and a turn-in-place over a standard obstacle are shown in Figures 2 and 3 respectively. The obstacle in both cases was a standard wood 4X4 (8.75cmX8.75cm), and was staked in place in order to prevent it from moving while under the wheels. The obstacle was placed 0.6m in front with respect to the center of the rover for the drive tests, and centered between the front wheels for the turn test.

The tests demonstrated that the average localization error compared to ground truth over all of the driving runs was 6.31% (two runs were treated as outliers and not included due to results that could not be replicated in further tests). Scatterplot results (constant percentage error with respect to distance traveled) presented in the Summary section indicate that a portion of the overall error can be traced to an inaccurate effective wheel diameter for derivation of the odometry input to the EKF. The average heading error compared to ground truth over all of the runs was 1.92° with an average slip of 2.83% of the angle turned with respect to the ground truth. Once again, the inaccurate effective wheel diameter will have an impact on this error.

## EKF Test Matrix

Case #	Test Case	Objectives
EKF: Rover Baseline		
1	Drive 1 m	Test forward drive
2	Drive -1 m	Test backward drive
3	Turn-in-Place 30°	Test right turn
4	Turn-in-Place -60°	Test left turn
5	Drive Arc 1 m, 45°	Test arc drive right
6	Drive Arc 1 m, -45°	Test arc drive left
EKF: No Motion		
1	Heading 0°	Test bias drift
2	Heading 90°	Test bias drift
3	Heading 180°	Test bias drift
4	Heading 270°	Test bias drift
EKF: Odometry		
1	Drive 1 m	Test short drive forward
2	Driver 3 m	Test longer drive forward
3	Drive -1 m	Test short drive backward
4	Drive -3 m	Test longer drive backward
5	Drive Arc 1 m, 45°	Test short arc drive right
6	Drive Arc 2 m, 45°	Test longer arc drive right
7	Drive Arc 1 m, -45°	Test short arc drive left
8	Drive Arc 2 m, -45°	Test longer arc drive left
9	Turn-in-Place 45°	Test turn-in-place right
10	Turn-in-Place -45°	Test turn-in-place left
11	Turn-in-Place 45°, and then 320°	Test sequential right turns-in-place
12	Turn-in-Place -45°, and then -320°	Test sequential left turns-in-place
13	Drive 1.5 m with standard obstacle on right	Test short drive with obstacle
14	Drive 3 m with standard obstacle on right	Test longer drive with obstacle
15	Drive Arc 3 m, 45° with standard obstacle on right	Test longer arc drive with obstacle
16	Turn-in-Place 180° with standard obstacle in center	Test turn-in-place with obstacle
17	Turn-in-Place 5°	Test short turn-in-place right
18	Turn-in-Place -5°	Test short turn-in-place left

Case #	Test Case	Objectives
EKF: Turn-in-Place		
1	Turn-in-Place 45°	Test turn-in-place right
2	Turn-in-Place -45°	Test turn-in-place left
3	Turn-in-Place 180° with standard obstacle in center	Test turn-in-place with obstacle
4	Turn-in-Place 5°	Test short turn-in-place right
5	Turn-in-Place -5°	Test short turn-in-place left
EKF: Sequential Path		
1	Zig-Zag Drive	Test sequence of straight forward drives and turns-in-place
2	Square Drive	Test sequence of straight drives and turns-in-place in square pattern
3	S-Arc Drive	Test sequence of arc drives right followed by sequence of arc drives left



Figure 1. EKF test setup. Leica TotalStation is in background and Rocky8 rover with four fiducial targets is in foreground.



Figure 2. Test setup for driving over a standard obstacle. Left: Side view; Right: front view.



Figure 3. Test setup for turn-in-place over a standard obstacle.

### Format for Test Results

The format for the summary table of results for each test is as follows (example shown)

Test number	Error compared to commanded	Error compared to TotalStation ground truth
Command	Move(1,0)	
Commanded		
Theory		
X	1	0.0571
Y	0	0.0131
Heading	0	0.709
EKF		
X	0.9997	-0.0003
Y	0.0126	0.0126
Heading	1.4036	1.4036
Rover Odometry		
Odo		
X	0.9999	0
Y	0	0
Heading	0	0
TotalStation Ground Truth		
Total St.		
X	1.0571	
Y	0.0131	
Heading	0.709	
Percent Error		
	1.260357	5.740218 EKF
		5.858344 Commanded

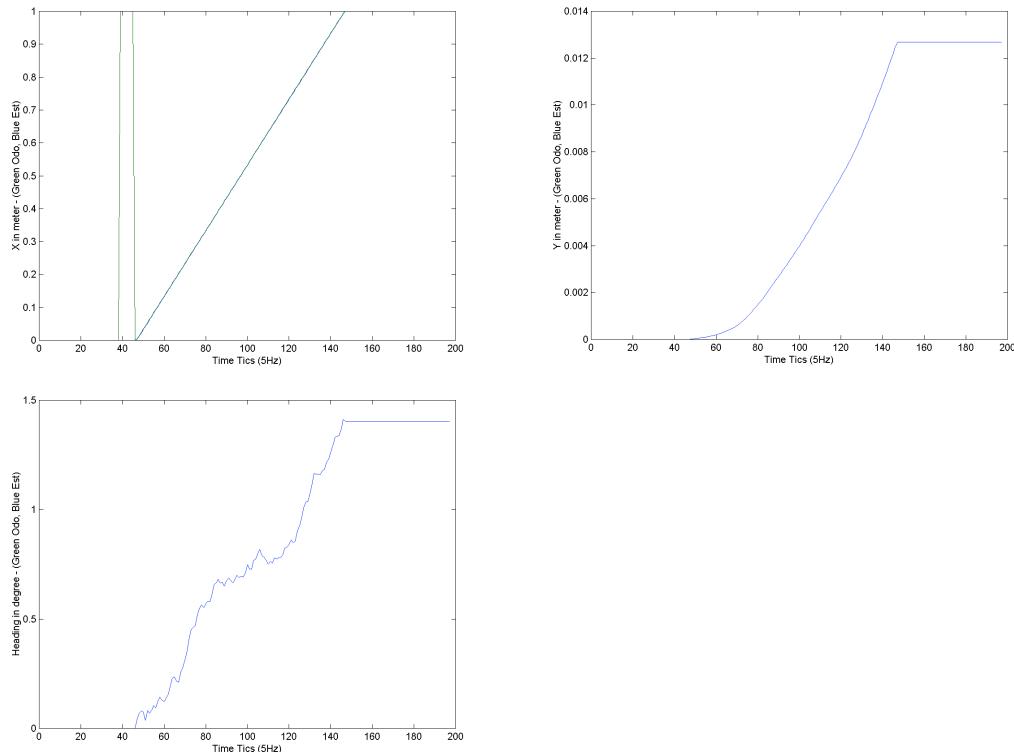
The percent error will be measured with relation to the total distance traveled for traverses and will be the angular deviation (instead of percent error) for turns.

The presentation format for graphs is to plot the rover odometry in green and the EKF in blue. The x-axis is the time in ticks, where a tick is related to the sample rate (i.e. 5Hz), and the y-axis is the value of the variables that were logged for the test.

### 4.1.2 Rover Baseline Tests

This series of tests was run to get a baseline assessment of the Rocky8 rover operational envelope under CLARAty. The interface used at this time didn't report gyro bias for this series of tests. The presentation order for results in this series of tests will be the X-position, Y-position, and Heading (green is rover odometry, blue is EKF).

#### Test1: Drive 1 m



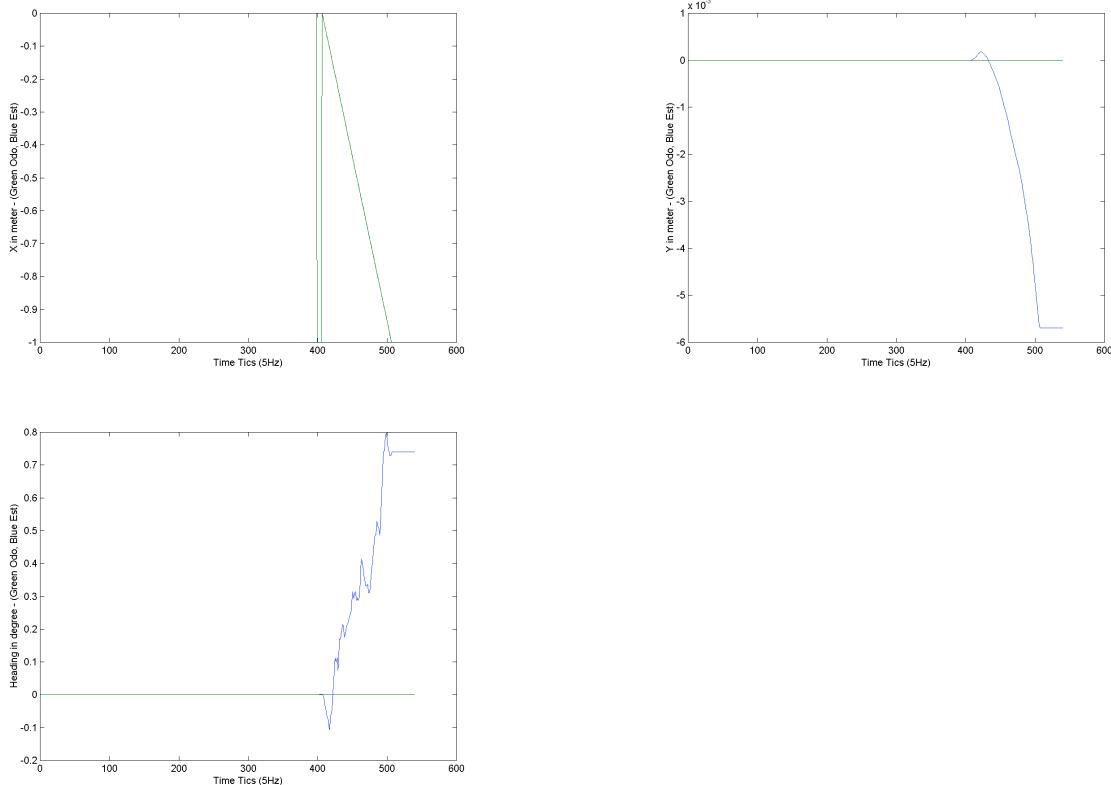
	Test1	E1	E2
Move(1,0)			
Theory			
X	1		0.0571
Y	0		0.0131
Heading	0		0.709
EKF			
X	0.9997	-0.0003	0.0574
Y	0.0126	0.0126	0.0005
Heading	1.4036	1.4036	-0.6946
Odo			
X	0.9999	0	
Y	0	0	
Heading	0	0	
Total St.			
X	1.0571		
Y	0.0131		
Heading	0.709		

## **EKF Test Report**

---

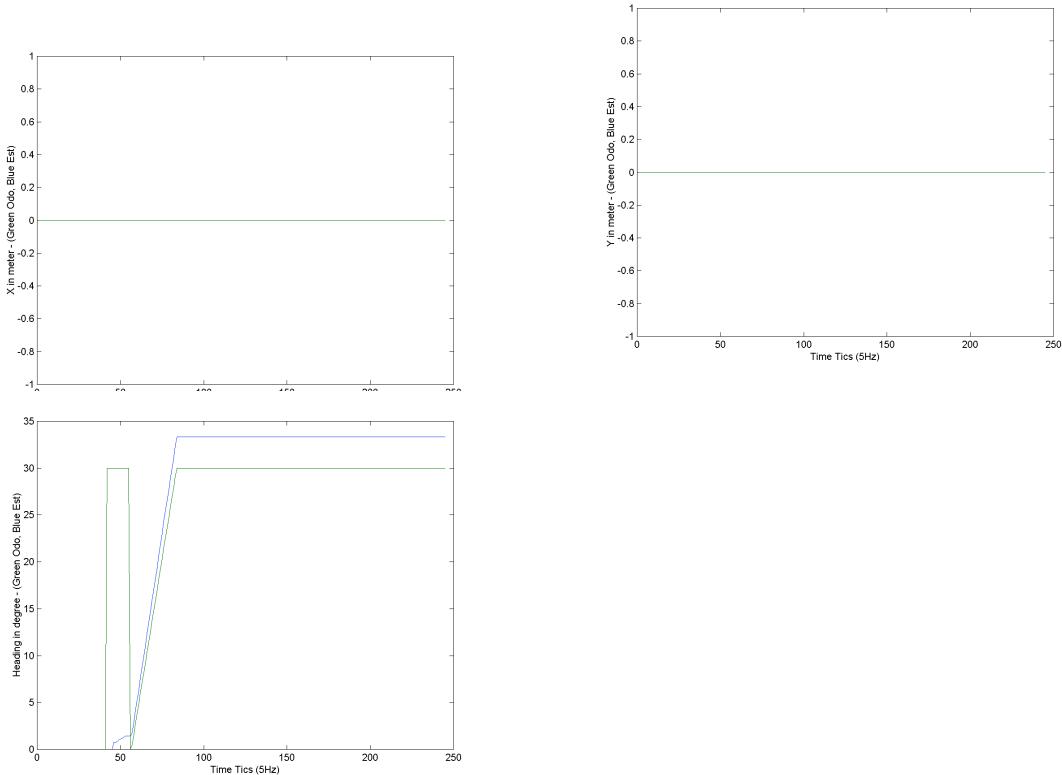
1.260357 5.740218 EKF  
5.858344 Commanded

**Test2: Drive -1 m**



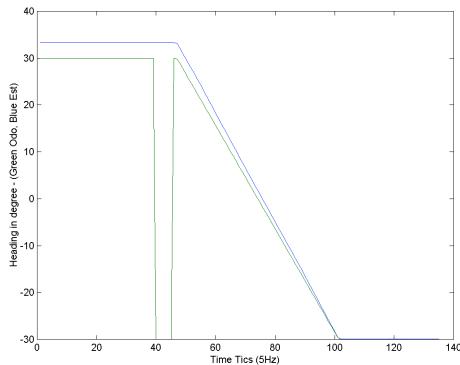
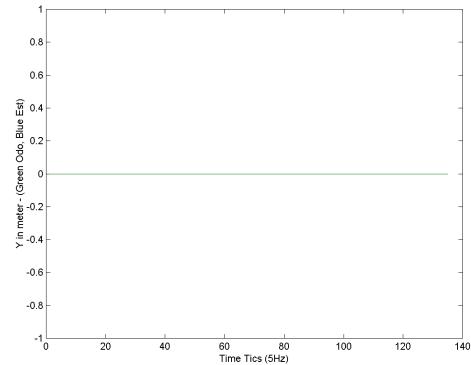
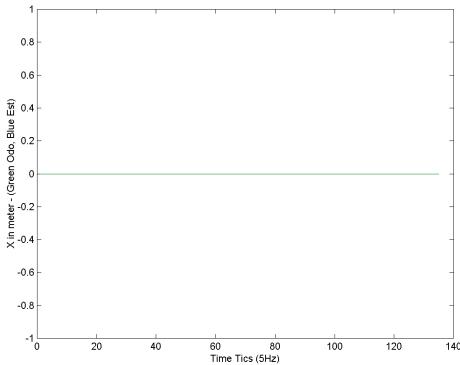
Test2:	E1	E2
Move(-1,0)		
Theory		
X	-1	-0.0576
Y	0	0.0047
Heading	0	-0.139
EKF		
X	-0.9997	0.0003
Y	-0.0056	-0.0056
Heading	0.7398	0.7398
Odo		
X	-100	0
Y	0	0
Heading	0	0
Total St.		
X	-1.0576	
Y	0.0047	
Heading	-0.139	
Overall Error:	0.560803	5.880901 EKF
		5.779144 Commanded

**Test3: Turn-in-Place 30°**



Test3	E1	E2
Move(0,30)		
Theory		
X	0	0.004
Y	0	0.011
Heading	30	2.077
EKF		
X	0	0.004
Y	0	0.011
Heading	33.348	3.348
Odo		
X	0	0
Y	0	0
Heading	30	0
Total St.		
X	0.004	
Y	0.011	
Heading	32.077	
Overall Error:	0	0.011705 EKF 0.011705 Commanded

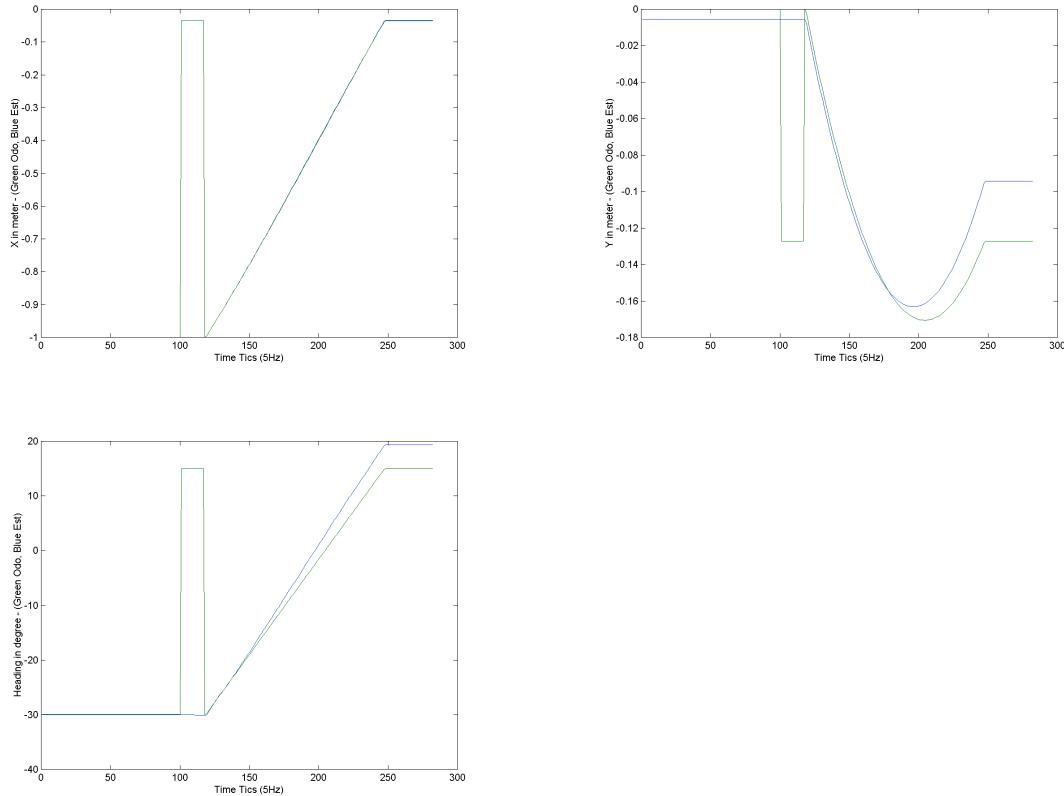
**Test4: Turn-in-Place -60°**



Test4 Move(0,-60) E1  
Theory

X	0	0.012
Y	0	0.0149
Heading	-60	-2.71
EKF		
X	0	0.012
Y	0	0.0149
Heading	-63.27	-3.27
Odo		0.56
X	0	0
Y	0	0
Heading	-30	0
Total St.		
X	0.012	
Y	0.0149	
Heading	-62.71	
Overall Error:	0	0.019131 EKF 0.019131 Commanded

**Test5: Drive Arc 1 m, 45°**



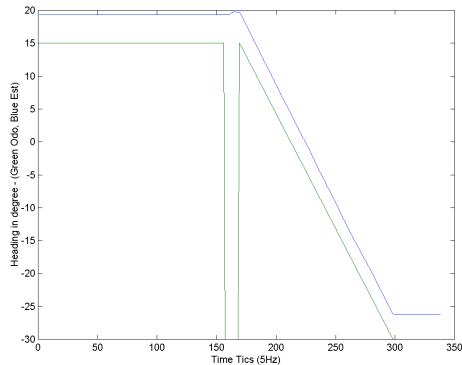
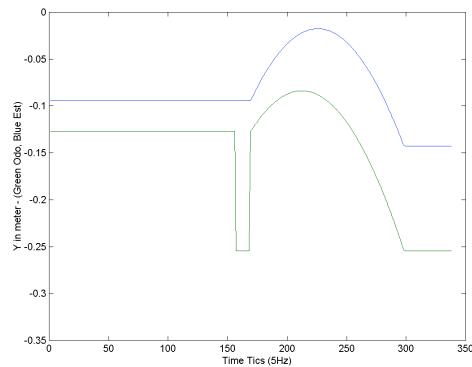
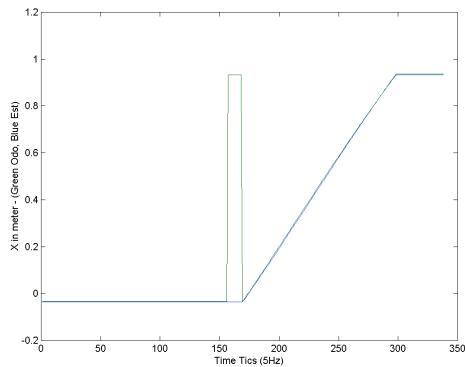
Test5:	E1	E2
Theory	Move(1,45)	

X	0.9001	0.06167	
Y	0.3728	0.01705	
Heading	45	1.45	
<b>EKF</b>			
X	0.8793	-0.0208	0.08247
Y	0.4041	0.0313	-0.01425
Heading	49.274	4.274	-2.824
<b>Odo</b>			
X	0.9001	0	
Y	0.3728	0	
Heading	45	0	
<b>Total St.</b>			
X	0.96177		
Y	0.38985		
Heading	46.45		

3.758098 8.369207 EKF

6.398352 Commanded

**Test6: Drive Arc 1m , -45°**



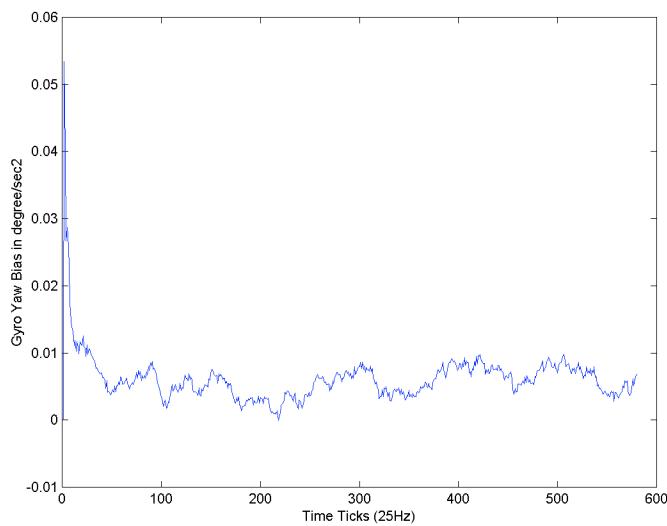
Test6:	E1	E2
Move(1,-45)		
Theory		
X	0.9001	0.04577
Y	-0.3728	-0.03083
Heading	-45	-1.62
EKF		
X	0.9011	0.001 0.04477
Y	-0.3675	0.0053 -0.03613
Heading	-45.52	-0.52 -1.1
Odo		
X	0.9001	0
Y	-0.3728	0
Heading	-45	0
Total St.		
X	0.94587	
Y	-0.40363	
Heading	-46.62	

0.539351 5.753025 EKF  
5.518498 Commanded

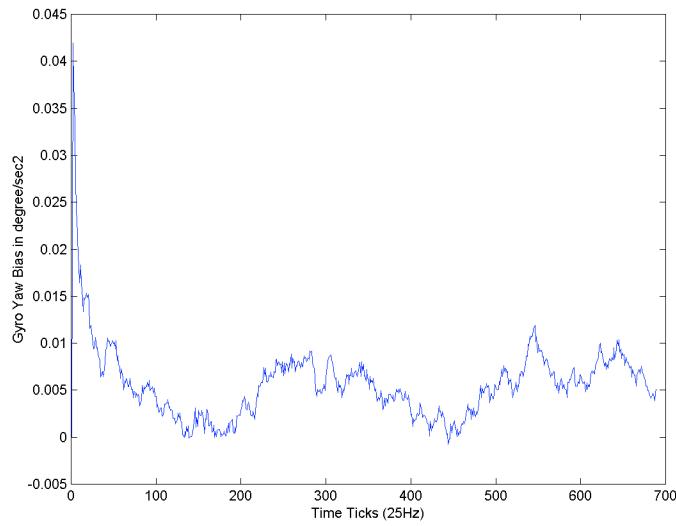
#### 4.1.3 EKF No Motion Test

This test was designed to test the gyro yaw bias while the rover was not in motion. This is the input to the first stage of the EKF algorithm and is used for an estimate of the gyro yaw bias during any subsequent movement.

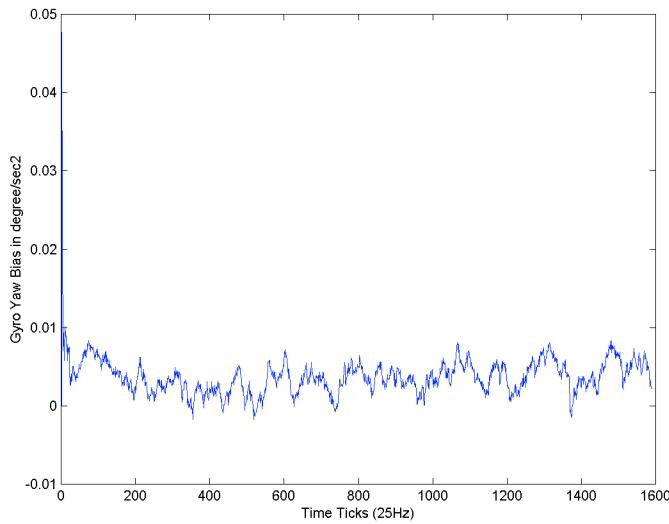
##### Test1: Heading 0°



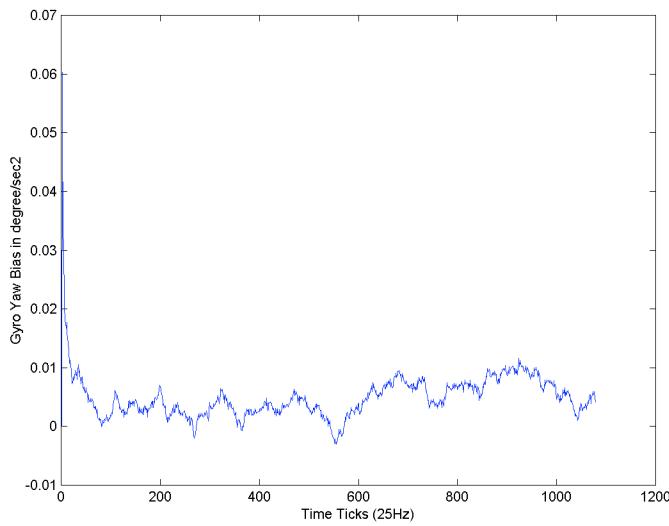
##### Test2: Heading 90°



**Test3: Heading 180°**



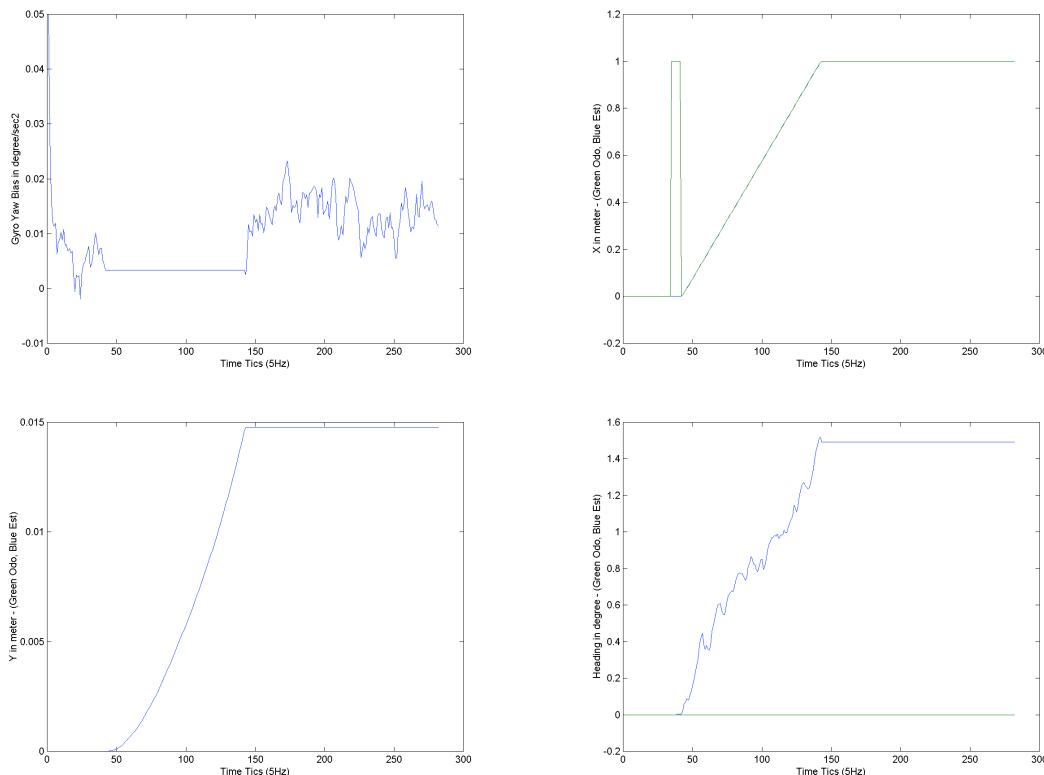
**Test4: Heading 270°**



#### 4.1.4 Odometry Tests

These tests were originally designed to test the system with no second stage EKF, but due to the issue noted in the Executive Summary, the tests had both outputs available.

##### Test1: Drive 1 m



Test1                          E1

E2

Move(1,0)

Theory

X	1	0.0834
Y	0	0.0032
Heading	0	0.3807

EKF

X	0.9999	-1E-04	0.0835
Y	0.0147	0.0147	-0.0115
Heading	1.4926	1.4926	-1.1119

Odo

X	0.9999	0
Y	0	0
Heading	0	0

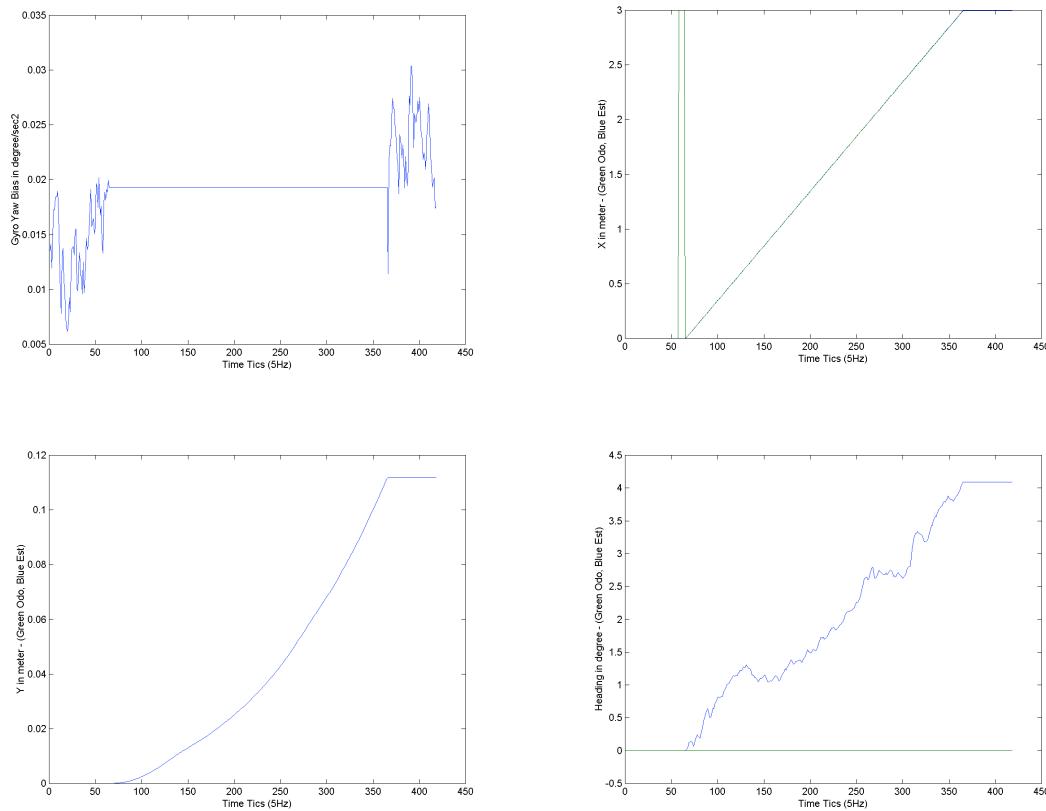
Total St.

X	1.0834
Y	0.0032
Heading	0.3807

Overall Error:              1.470034    8.42882 EKF

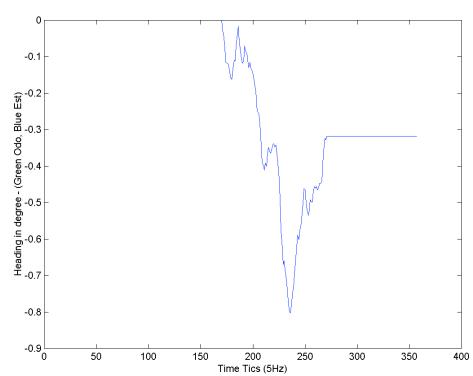
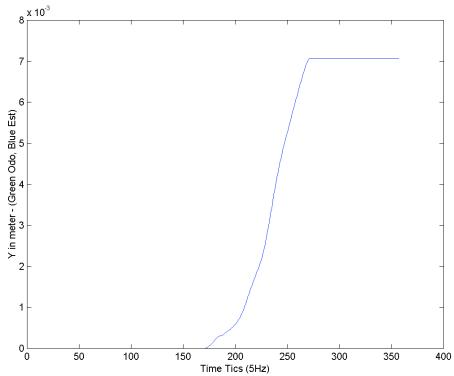
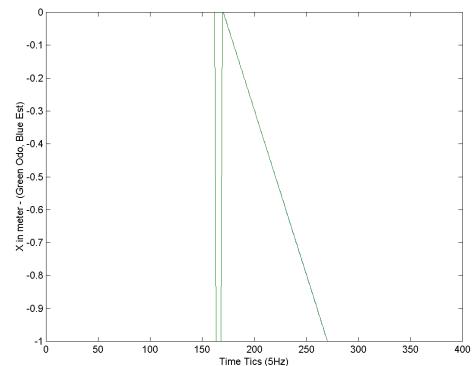
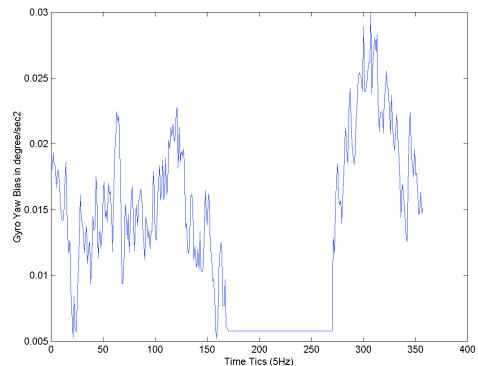
                              8.346137 Commanded

### Test2: Drive 3 m



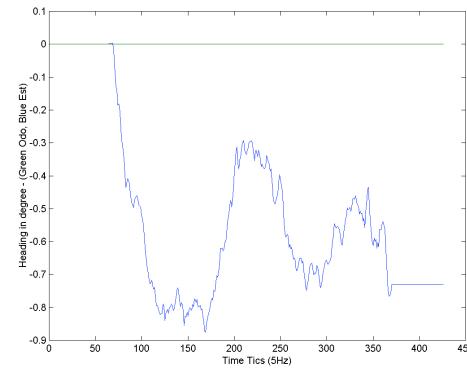
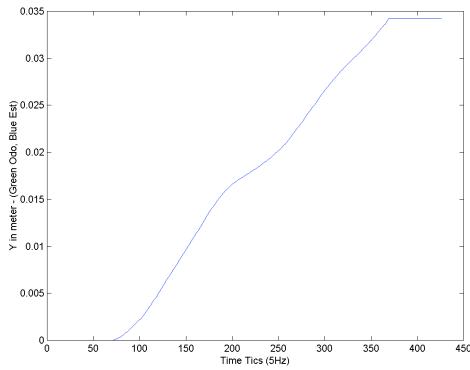
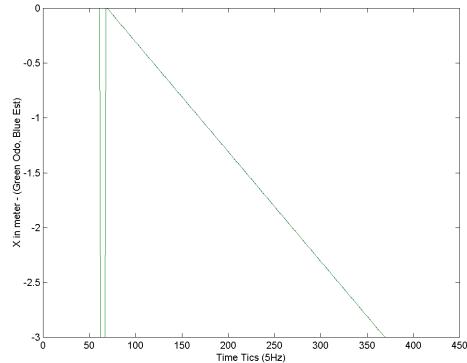
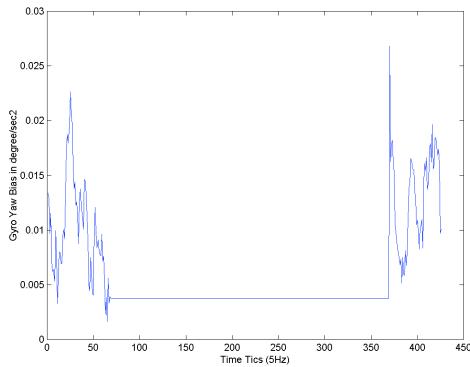
Test2	E1	E2	
Move(3,0)			
Theory			
X	3	0.1798	
Y	0	0.0393	
Heading	0	0.94822	
EKF			
X	2.99711	-0.00289	0.182687
Y	0.11173	0.111734	-0.07243
Heading	4.08948	4.08948	-3.14126
Odo			
X	3	0	
Y	0	0	
Heading	0	0	
Total St.			
X	3.1798		
Y	0.0393		
Heading	0.94822		
Overall Error:	3.72571	6.550761 EKF	
		6.13483 Commanded	

### Test3: Drive -1 m



Test3	E1	E2
Move(-1,0)		
Theory		
X	-1	-0.0337
Y	0	0.0071
Heading	0	-0.32123
EKF		
X	-0.9997	0.0003
Y	0.007	0.007
Heading	-0.3183	-0.3183
Odo		
X	0.9999	0
Y	0	0
Heading	0	0
Total St.		
X	-1.0337	
Y	0.0071	
Heading	-0.32123	
Overall Error	0.700643	3.400015 EKF 3.44398 Commanded

### Test4: Drive -3 m



Test4                    E1                    E2  
Move(-3,0)

Theory

X	-3	-0.2046
Y	0	0.0081
Heading	0	-0.13287

EKF

X	-2.999	0.001	-0.2056
---	--------	-------	---------

Y	0.034	0.034	-0.0259
---	-------	-------	---------

Heading	0.731	0.731	-0.86387
---------	-------	-------	----------

Odo

X	-3	0
---	----	---

Y	0	0
---	---	---

Heading	0	0
---------	---	---

Total St.

X	-3.2046
---	---------

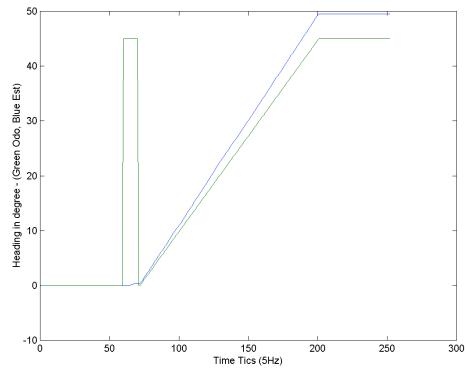
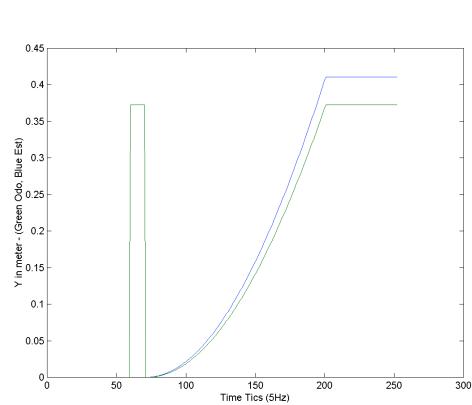
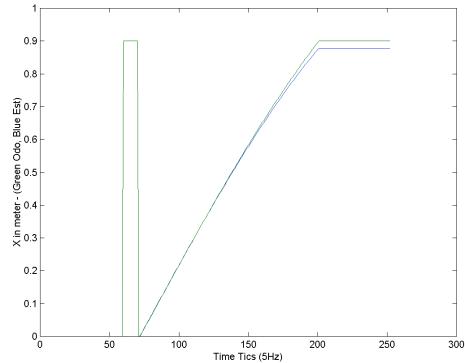
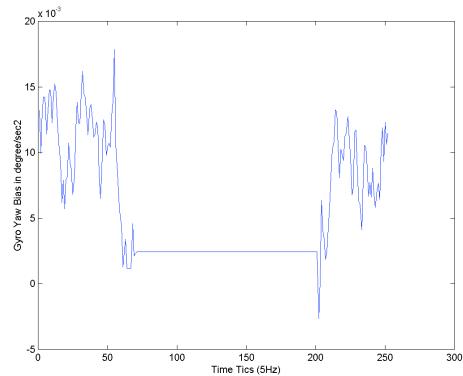
Y	0.0081
---	--------

Heading	-0.13287
---------	----------

Overall Error        1.133823 6.907498 EKF

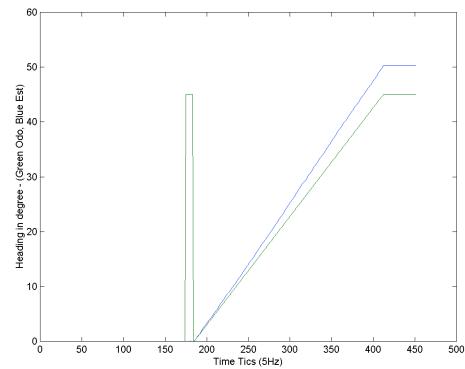
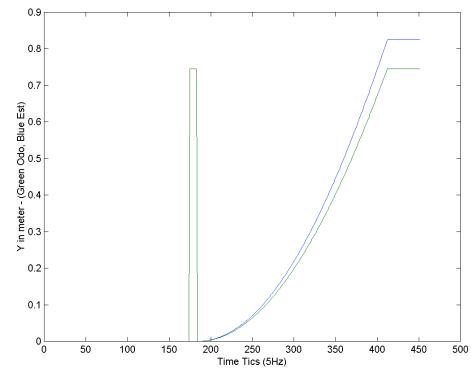
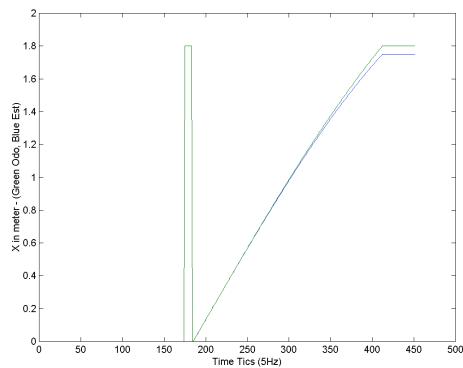
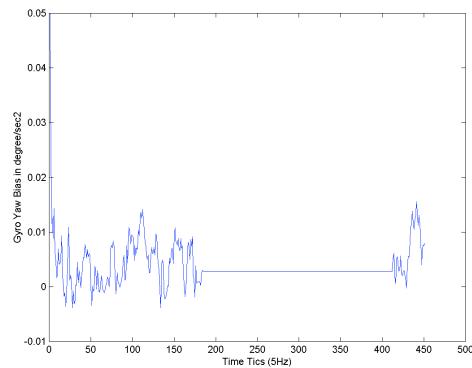
6.825342 Commanded

**Test5: Drive Arc 1 m, 45°**



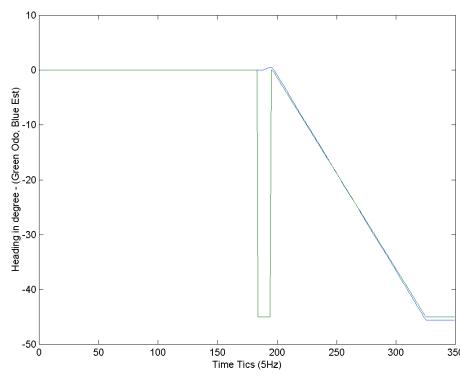
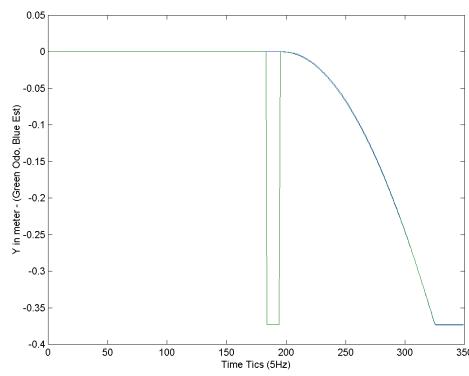
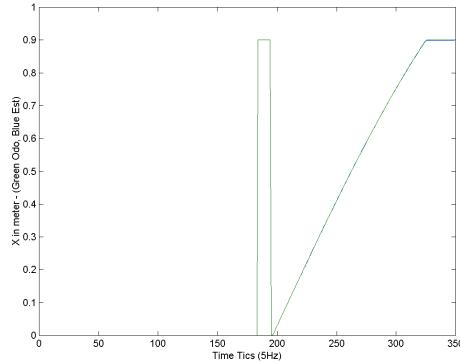
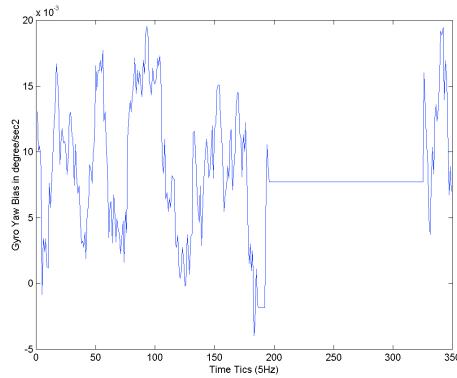
Test5	E1	E2
Move(1,45)		
Theory		
X	0.9007	0.1358
Y	0.3731	-0.1489
Heading	45	2.64959
EKF		
X	0.877	-0.0237
Y	0.41	0.0369
Heading	49.5	4.5 -1.85041
Odo		
X	0.9	0
Y	0.372	0
Heading	0	0
Total St.		
X	1.0365	
Y	0.2242	
Heading	47.64959	
Overall Error	4.385544	24.48712 EKF
		20.15263 Commanded

**Test 6: Drive Arc 2 m, 45°**



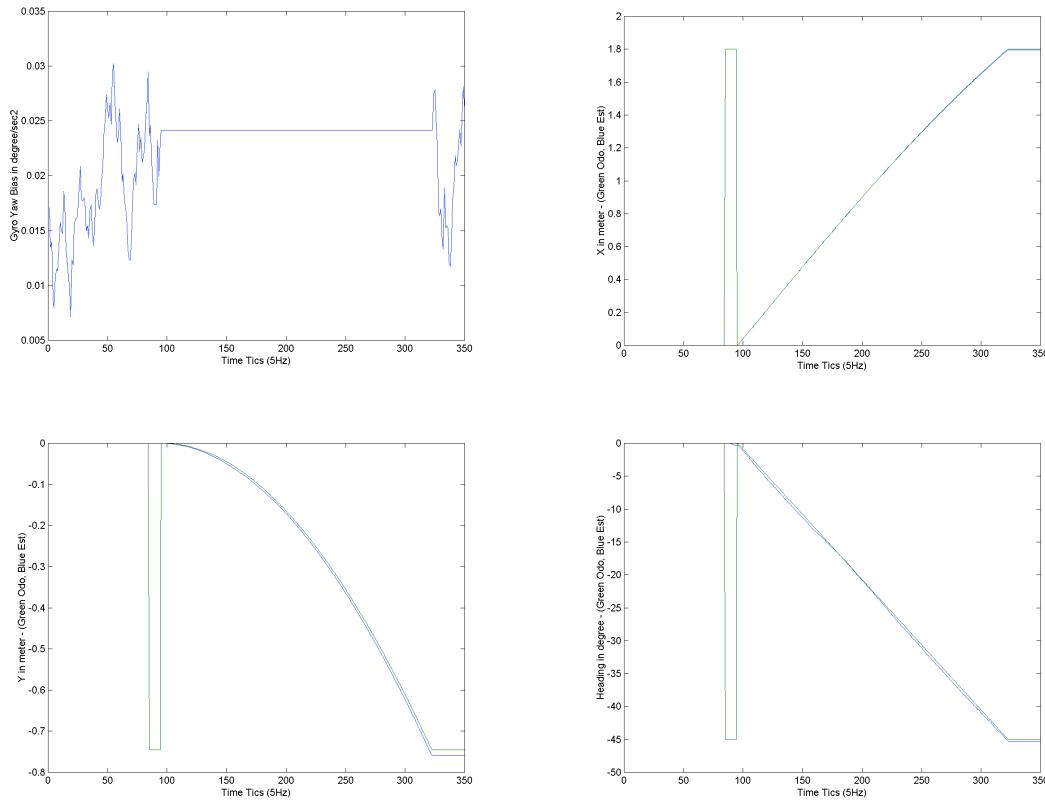
Test6	E1	E2
Move(2,45)		
Theory		
X	1.8015	-0.0435
Y	0.7462	-0.1341
Heading	45	1.93182
EKF		
X	1.7494	-0.0521
Y	0.8247	0.0785
Heading	50.25	5.25
Odo		-3.31818
X	1.8	0
Y	0.745	0
Heading	45	0
Total St.		
X	1.758	
Y	0.6121	
Heading	46.93182	
Overall Error	4.710801	10.63869 EKF
		7.048947 Commanded

**Test7: Drive Arc 1 m, -45°**



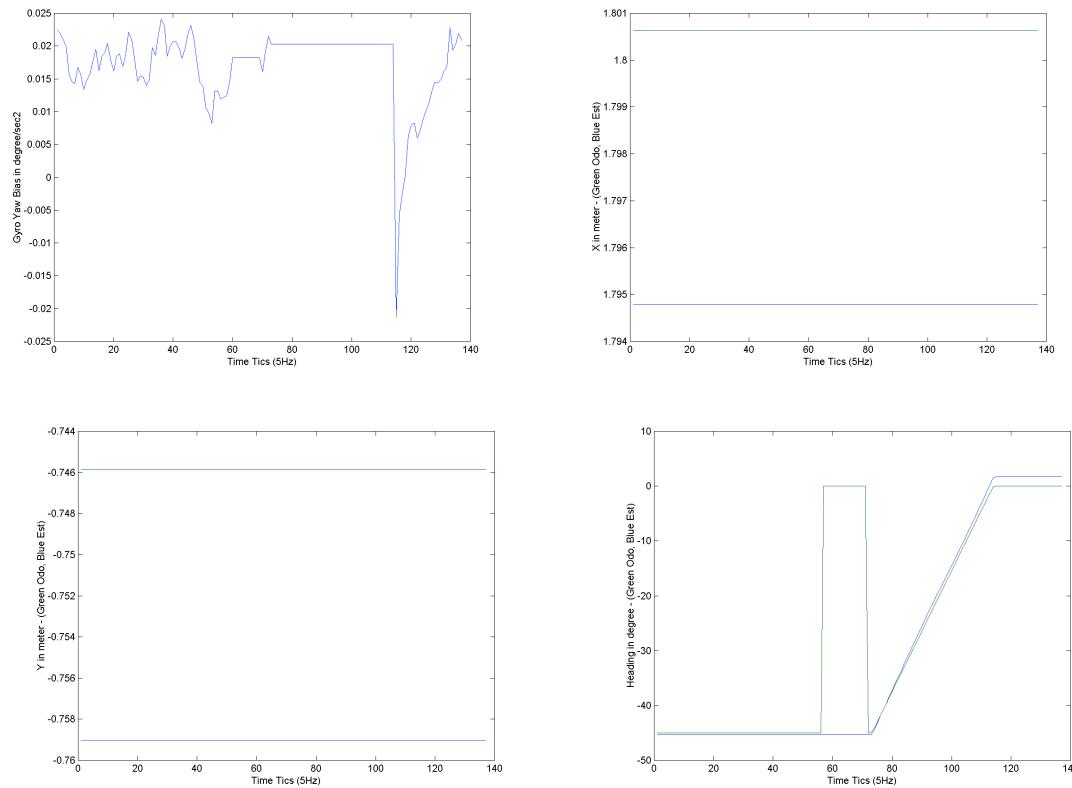
Test7	E1	E2
Move(1,-45)		
Theory		
X	0.9	0.294
Y	-0.373	0.0016
Heading	-45	-1.181
EKF		
X	0.898	-0.002
Y	-0.373	0
Heading	-45.61	-0.61
Odo		
X	0.9	0
Y	-0.372	0
Heading	-45	0
Total St.		
X	1.194	
Y	-0.3714	
Heading	-46.181	
Overall Error	0.2	29.60043 EKF 29.40044 Commanded

**Test8: Drive Arc 2 m, -45°**



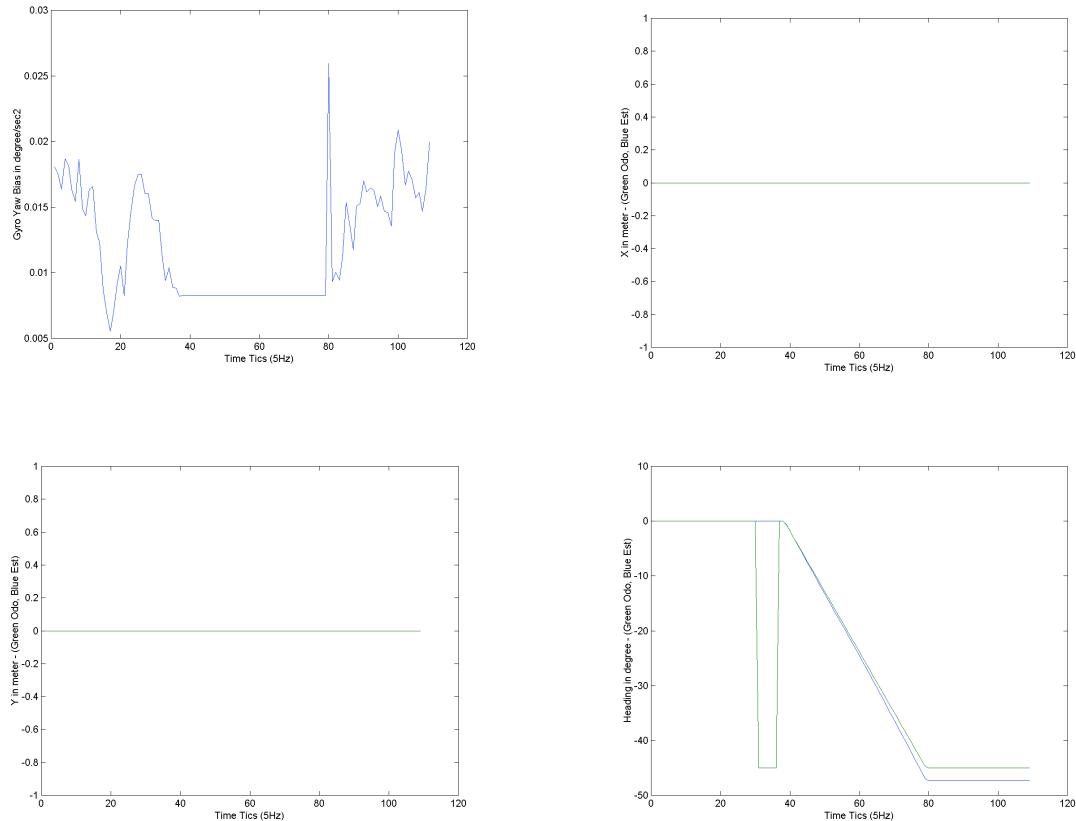
Test8	E1	E2
Move(2,-45)		
Theory		
X	1.801	0.118
Y	-0.746	-0.053
Heading	-45	-1.7767
EKF		
X	1.794	-0.007
Y	-0.759	-0.013
Heading	-45.3	-0.3
Odo		
X	1.8	0
Y	-0.745	0
Heading	-45	0
Total St.		
X	1.919	
Y	-0.799	
Heading	-46.7767	
Overall Error	0.738241	6.562202 EKF
		6.467805 Commanded

### Test9: Turn-in-place 45°



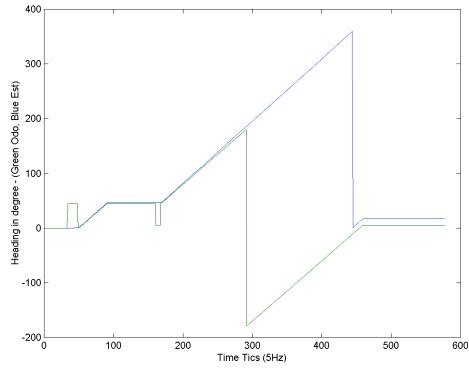
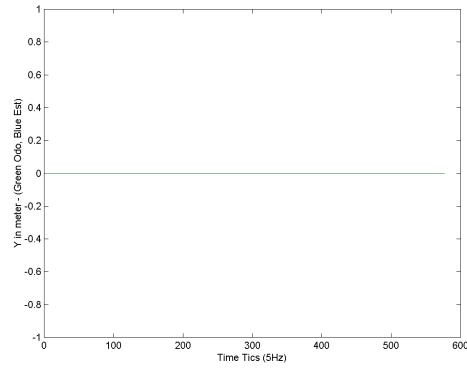
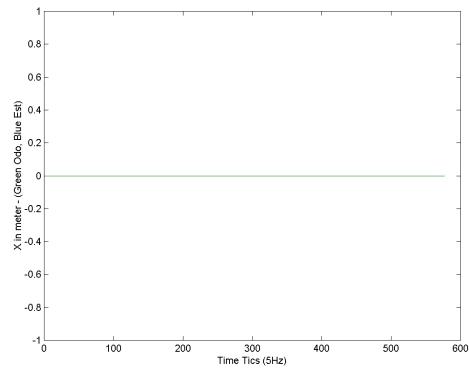
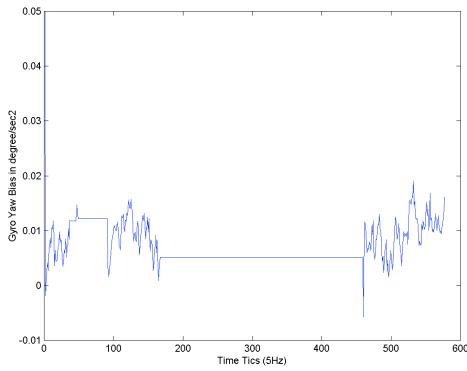
Test9	E1	E2
Move(0,45)		
Theory		
X	0	0.0047
Y	0	0.0032
Heading	45	1.2273
EKF		
X	0	0.0047
Y	0	0.0032
Heading	46.794	1.794 -0.5667
Odo		
X	0	0
Y	0	0
Heading	45	0
Total St.		
X	0.0047	
Y	0.0032	
Heading	46.2273	
Overall Error	0	0.005686 EKF 0.005686 Commanded

### Test10: Turn-in-place -45°



test10	E1	E2
Move(0,-45)		
Theory		
X	0	0.003
Y	0	0.004
Heading	-45	-1.373
EKF		
X	0	0.003
Y	0	0.004
Heading	-47.276	-2.276
Odo		
X	0	0
Y	0	0
Heading	-45	0
Total St.		
X	0.003	
Y	0.004	
Heading	-46.373	
Overall Error:	0	0.005 EKF 0.005 Commanded

**Test11: Turn-in-place 45° and then 320°**



**Test11      E1      E2**  
Move(0,45), Move(0,320)

**Theory**

X	0	-0.034
Y	0	-0.053
Heading	5	8.01

**EKF**

X	0	0	-0.034
---	---	---	--------

Y	0	0	-0.053
---	---	---	--------

Heading	16.6	11.6	-3.59
---------	------	------	-------

**Odo**

X	0	0
---	---	---

Y	0	0
---	---	---

Heading	5	0
---------	---	---

**Total St.**

X	-0.034
---	--------

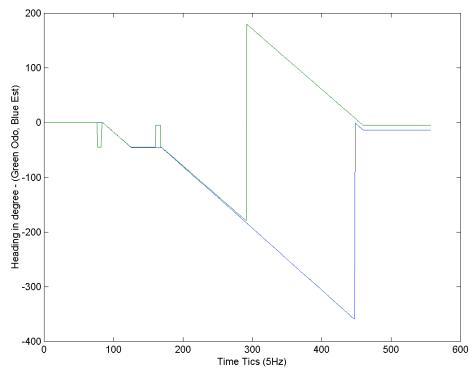
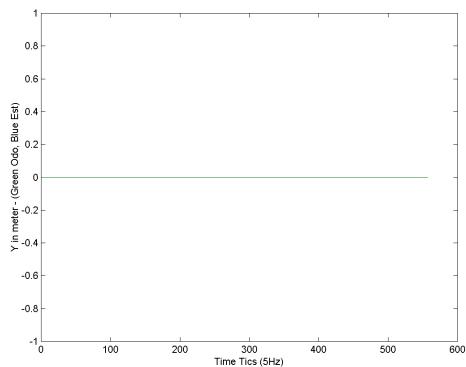
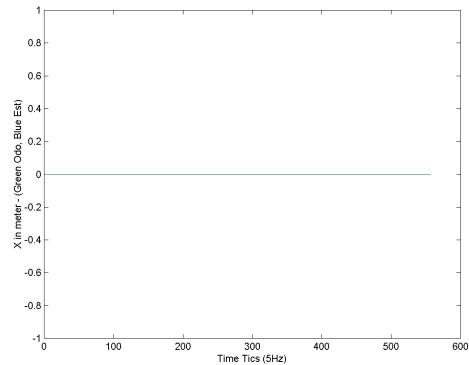
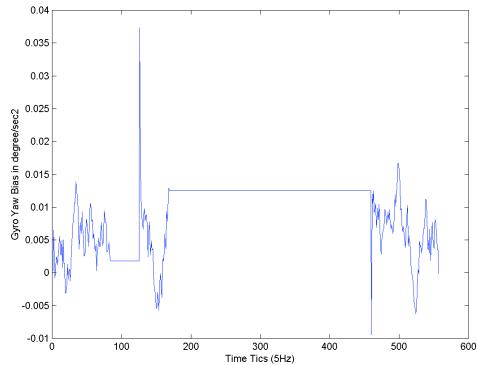
Y	-0.053
---	--------

Heading	13.01
---------	-------

Overall Error:

0 0.062968 EKF  
0.062968 Commanded

**Test12: Turn-in-place  $-45^\circ$  and then  $-320^\circ$**



Test12      E1      E2

Move(0,-45), Move(0,-320)

Theory

X	0	0
---	---	---

Y	0	0
---	---	---

Heading	-5	-5.93
---------	----	-------

EKF

X	0	0
---	---	---

Y	0	0
---	---	---

Heading	-13.666	-8.666
---------	---------	--------

Odo

X	0	0
---	---	---

Y	0	0
---	---	---

Heading	-5	0
---------	----	---

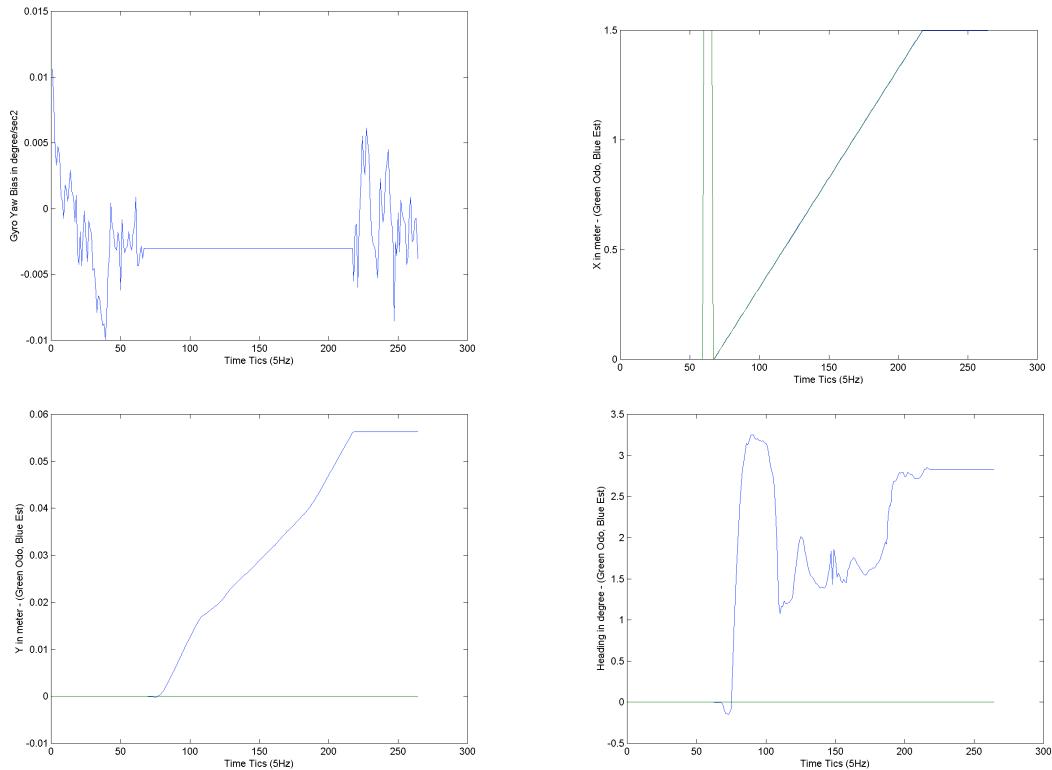
Total St.

X

Y

Heading	-10.93
---------	--------

**Test13: Drive 1.50 m with standard obstacle on right side (0.6 m from center)**



Test13

Move(1.5,0)

Theory

X	1.5	0.044
Y	0	0.0243
Heading	0	0.8247

EKF

X	1.498	-0.002	0.046
Y	0.056	0.056	-0.0317
Heading	2.828	2.828	-2.0033

Odo

X	1.5	0
Y	0	0
Heading	0	0

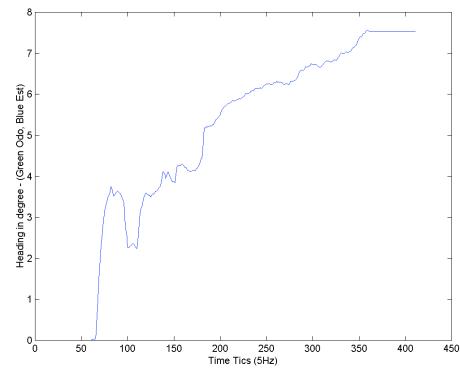
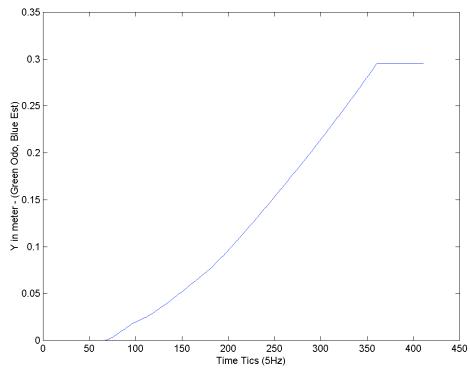
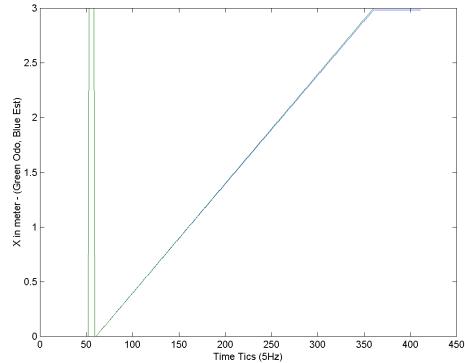
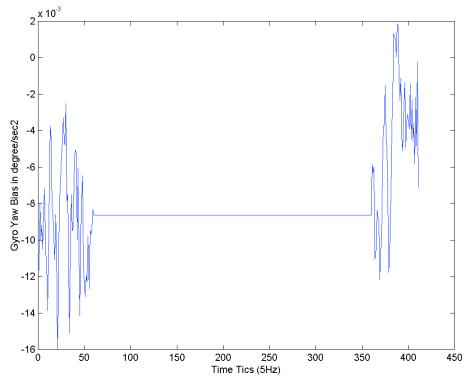
Total St.

X	1.544
Y	0.0243
Heading	0.8247

Overall Error 5.60357 3.724328 EKF

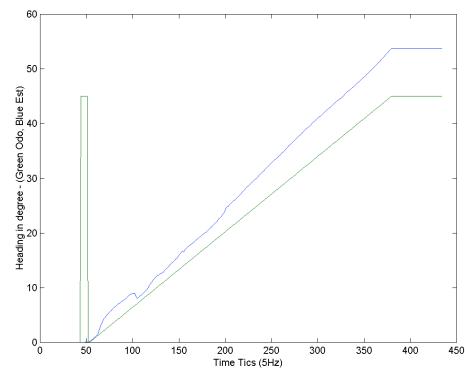
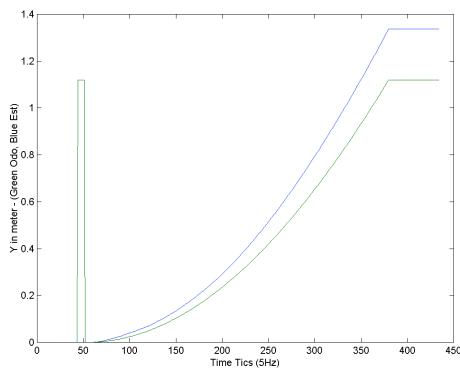
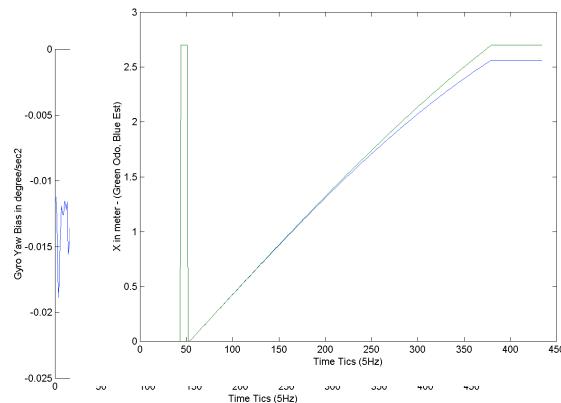
3.350947 Commanded

**Test14: Drive 3 m with standard obstacle on right side (0.6 m from center)**



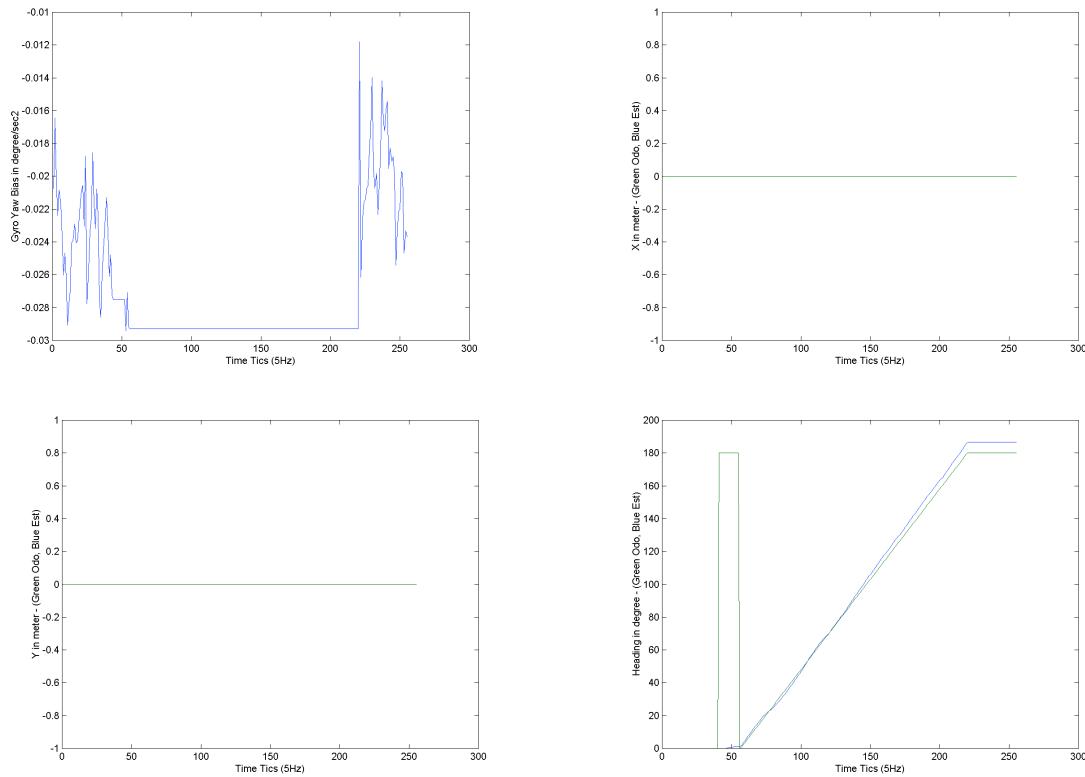
Test14	E1	E2
Move(3,0)		
Theory		
X	3	0.113
Y	0	0.1719
Heading	0	3.403
EKF		
X	2.983	-0.017
Y	0.295	0.295
Heading	7.532	7.532
Odo		
X	3	0
Y	0	0
Heading	0	0
Total St.		
X	3.113	
Y	0.1719	
Heading	3.403	
Overall Error	9.849647	5.967841 EKF
		6.857163 Commanded

**Test15: Drive Arc 3 m, 45° with standard obstacle on right side (0.6 m from center)**



Test15	E1	E2
Move(3,45)		
Theory		
X	2.7	-0.117
Y	1.119	-0.034
Heading	0	48.554
EKF		
X	2.563	-0.137
Y	1.336	0.217
Heading	53.72	53.72
Odo		
X	2.7	0
Y	1.118	0
Heading	0	0
Total St.		
X	2.583	
Y	1.085	
Heading	48.554	
Overall Error	8.554271	8.393185 EKF
		4.061335 Commanded

**Test16: Turn-in-place 180° with standard obstacle in center of front wheels**



Test16

Move(0,180)

E1

E2

Theory

X	0	0.25
Y	0	0.01
Heading	180	-0.934

EKF

X	0	0	0.25
Y	0	0	0.01
Heading	186.496	6.496	-7.43

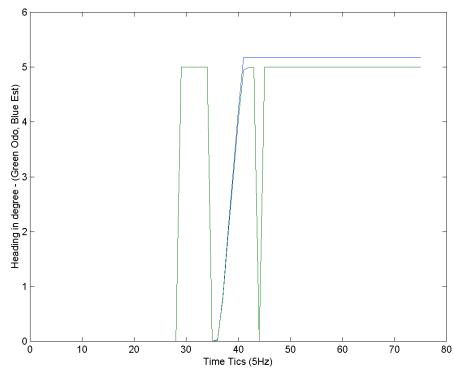
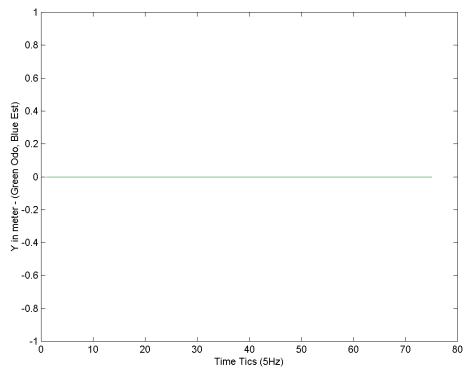
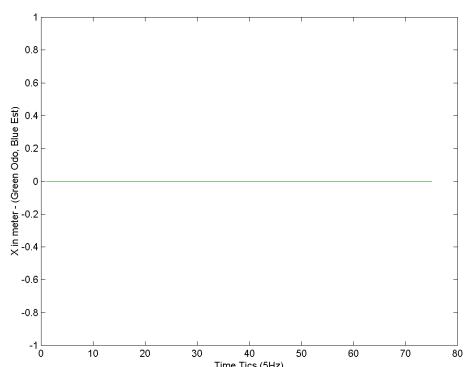
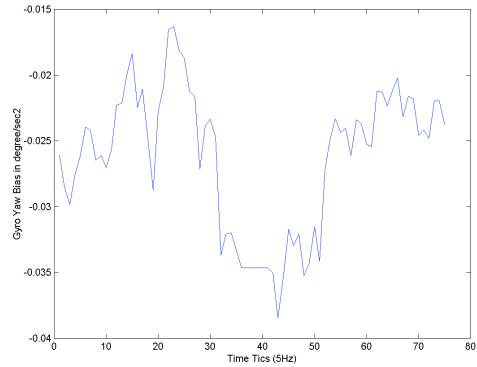
Odo

X	0	0
Y	0	0
Heading	180	0

Total St.

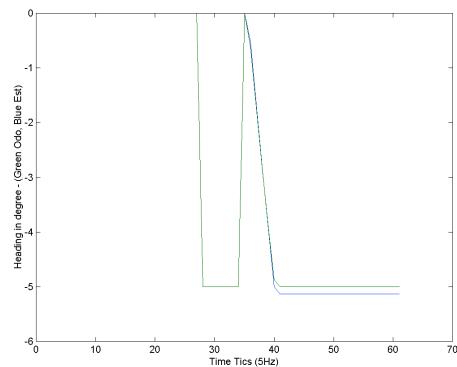
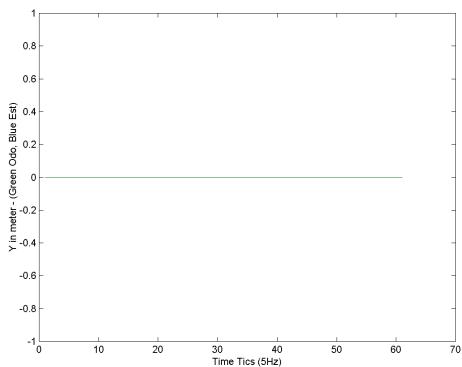
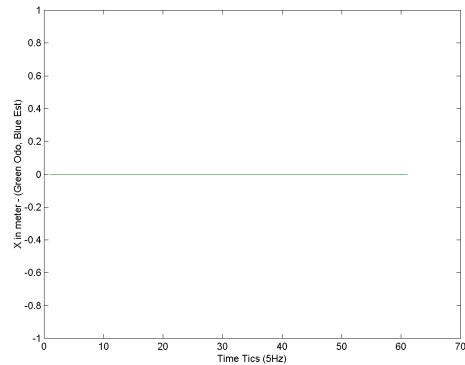
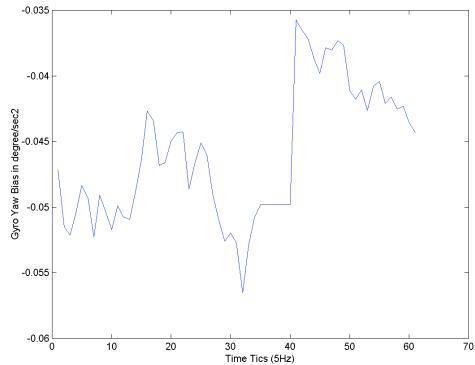
X	0.25	
Y	0.01	
Heading	179.066	0 0.2502 EKF 0.2502 Commanded

### Test17: Turn-in-place 5°



Test17		E1	E2
Move(0,5)			
Theory			
X	0	0.0011	
Y	0	-0.003	
Heading	5	0.126	
EKF			
X	0	0	0.0011
Y	0	0	-0.003
Heading	5.175	0.175	-0.049
Odo			
X	0	0	
Y	0	0	
Heading	5	0	
Total St.			
X	0.0011		
Y	-0.003		
Heading	5.126	0	0.003195 EKF
			0.003195 Commanded

**Test18: Turn-in-place -5°**

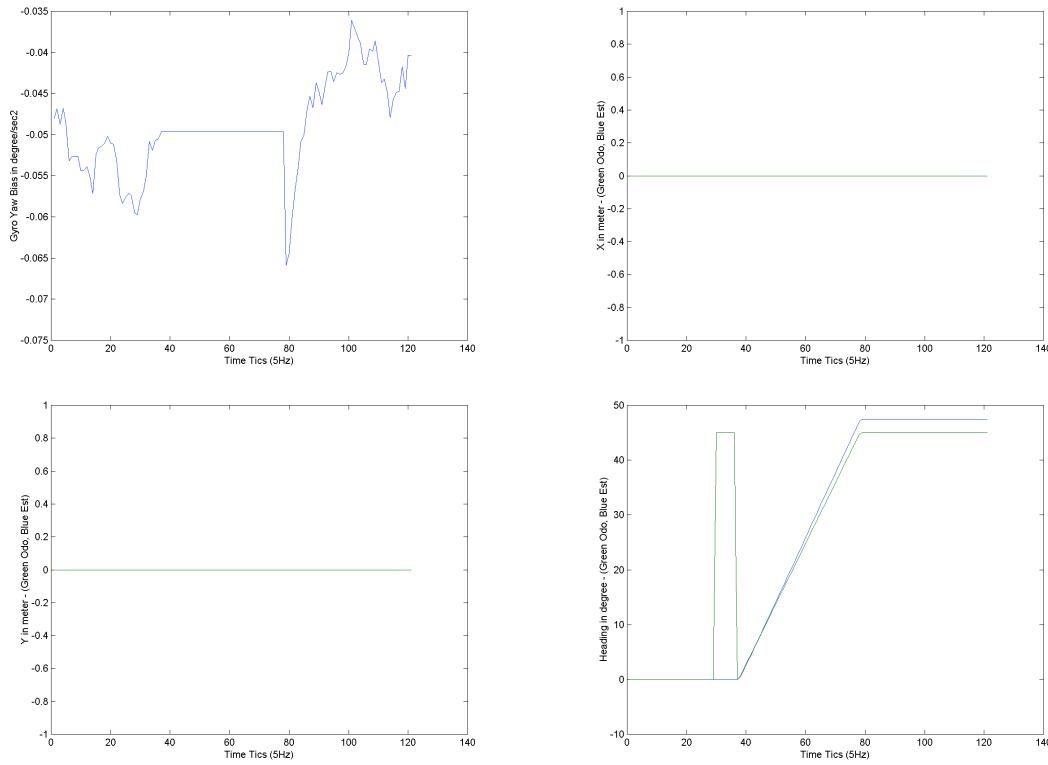


Test18	E1	E2
Move(0,-5)		
Theory		
X	0	0
Y	0	0
Heading	-5	-0.104
EKF		
X	0	0
Y	0	0
Heading	-5.132	-0.132
Odo		
X	0	0
Y	0	0
Heading	-5	0
Total St.		
X	0	0
Y	0	0
Heading	-5.104	0.028
Overall Error:		0 EKF 0 Commanded

#### 4.1.5 EKF Turn-in-place Tests

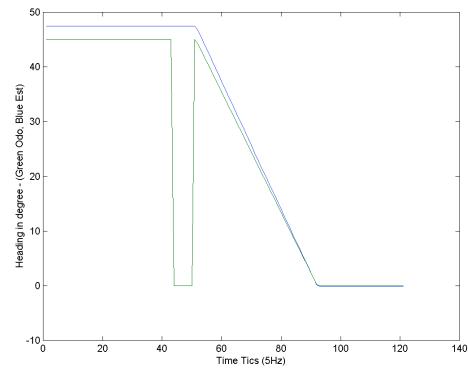
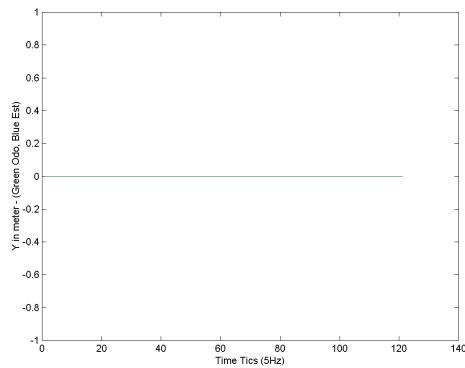
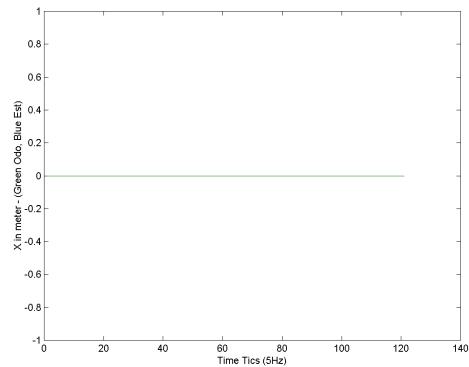
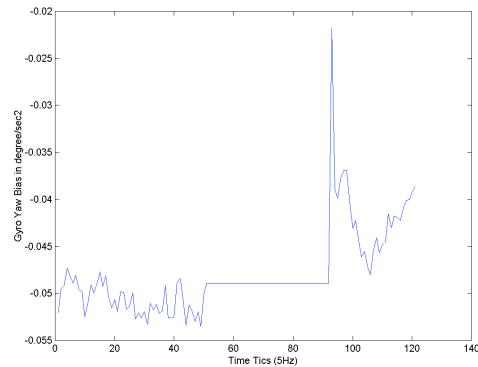
This series was designed to test the yaw gyro performance.

##### Test1: Turn-in-place 45°



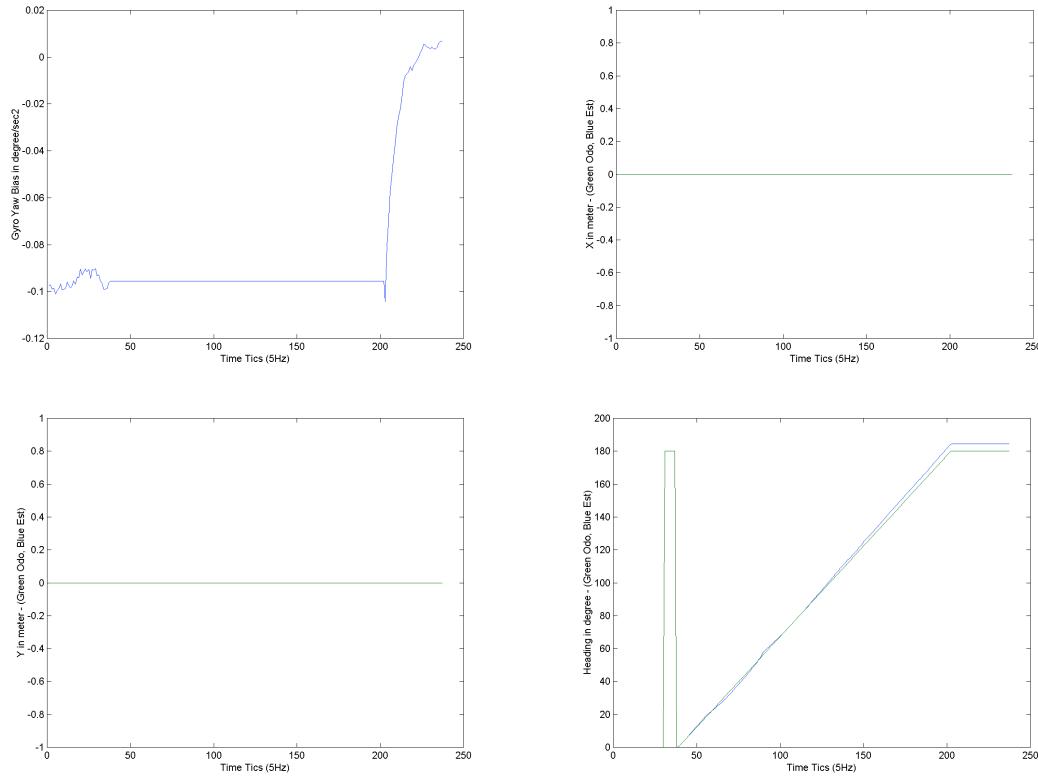
Test1		E1	E2
Move(0,45)			
<b>Theory</b>			
X	0		-0.0035
Y	0		0.0005
Heading	45		1.814
<b>EKF</b>			
X	0	0	-0.0035
Y	0	0	0.0005
Heading	47.444	2.444	-0.63
<b>Odo</b>			
X	0	0	
Y	0	0	
Heading	45	0	
<b>Total St.</b>			
X	-0.0035		
Y	0.0005		
Heading	46.814	0	0.003536 EKF
Overall Error:			0.003536 Commanded

**Test2: Turn-in-place -45°**



Test2	E1	E2
Move(0,-45)		
Theory		
X	0	0.0029
Y	0	0.0017
Heading	-45	-1.572
EKF		
X	0	0.0029
Y	0	0.0017
Heading	-45.093	-0.093
Odo		-1.479
X	0	0
Y	0	0
Heading	0	0
Total St.		
X	0.0029	
Y	0.0017	
Heading	-46.572	
Overall Error:	0	0.003362 EKF 0.003362 Commanded

### Test3: Turn-in-place 180° with Standard obstacle in between front wheels



Test3  
Move(0,180)

Theory

X	0	0.218
Y	0	0.0011
Heading	180	-0.87

EKF

X	0	0	0.218
Y	0	0	0.0011
Heading	184.36	4.36	-5.23

Odo

X	0	0
Y	0	0
Heading	180	0

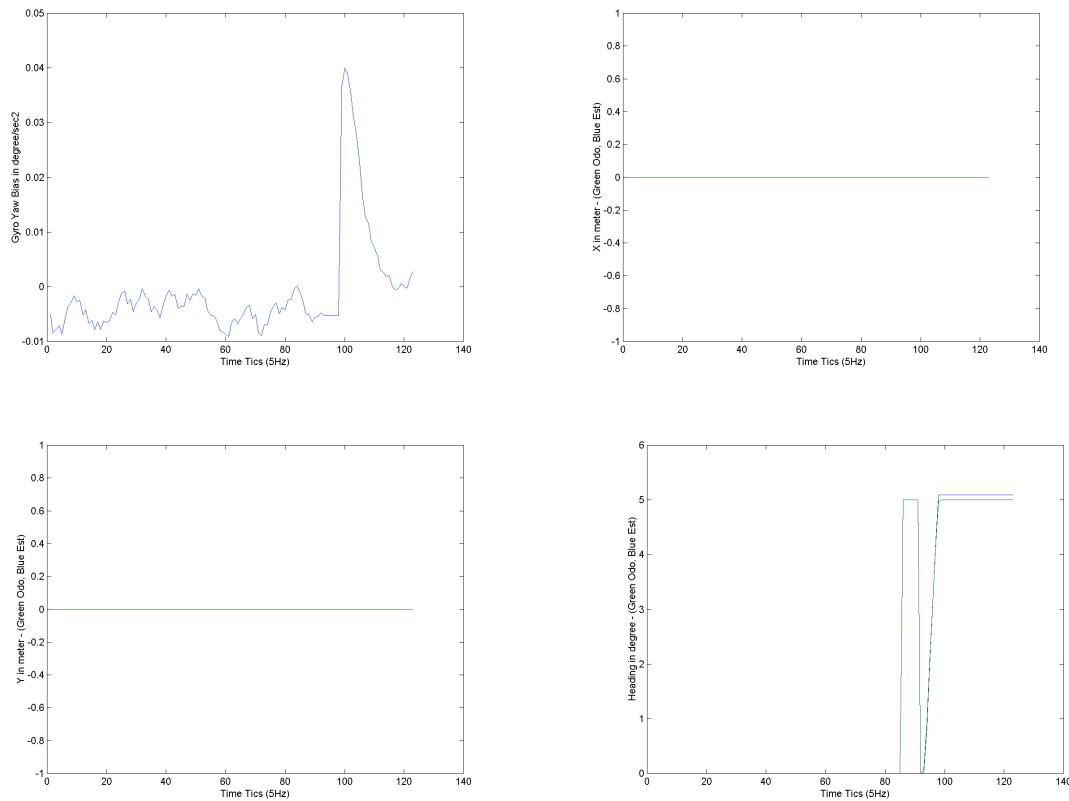
Total St.

X	0.218
Y	0.0011
Heading	179.13

Overall Error:

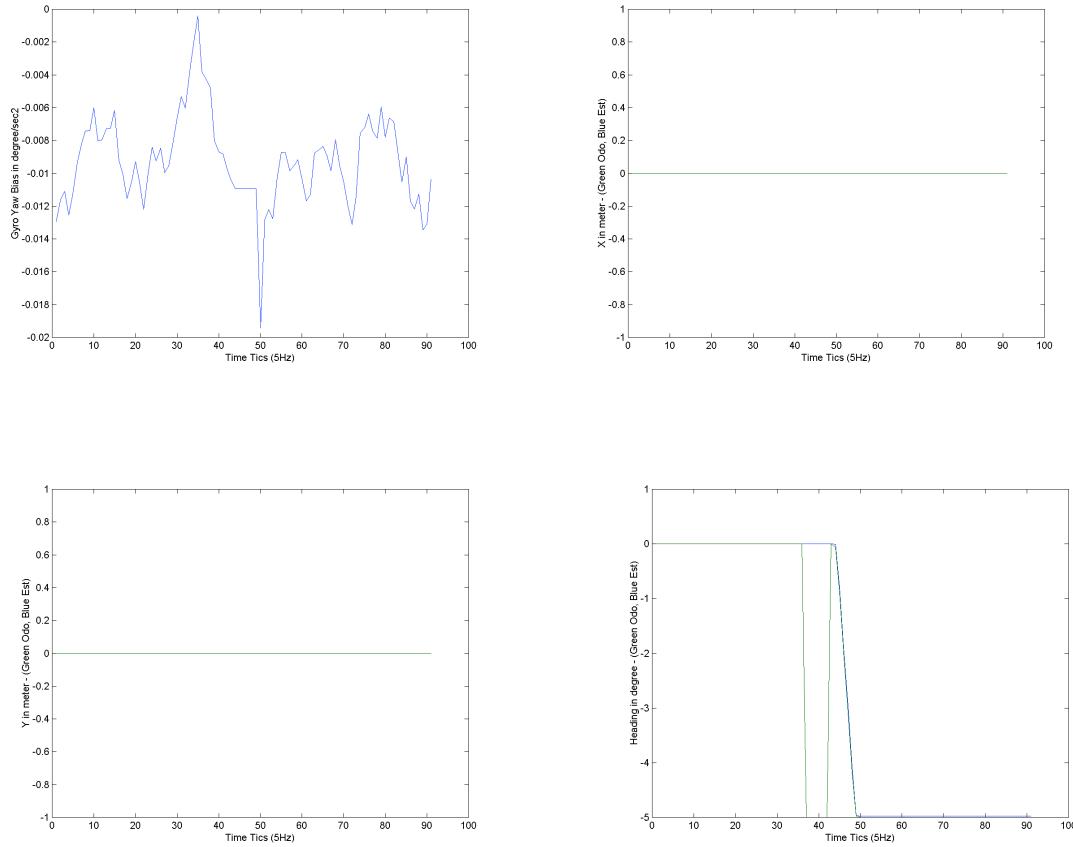
0 0.218003 EKF  
0.218003 Commanded

### Test4: Turn-in-place 5°



Test4	E1	E2
Move(0,5)		
Theory		
X	0	0
Y	0	-0.022
Heading	5	-0.0025
EKF		
X	0	0
Y	0	-0.022
Heading	5.095	0.095
Odo		
X	0	0
Y	0	0
Heading	5	0
Total St.		
X	0	
Y	-0.022	
Heading	4.9975	
Overall Error:	0	0.022 EKF 0.022 Commanded

### Test5: Turn-in-place -5°

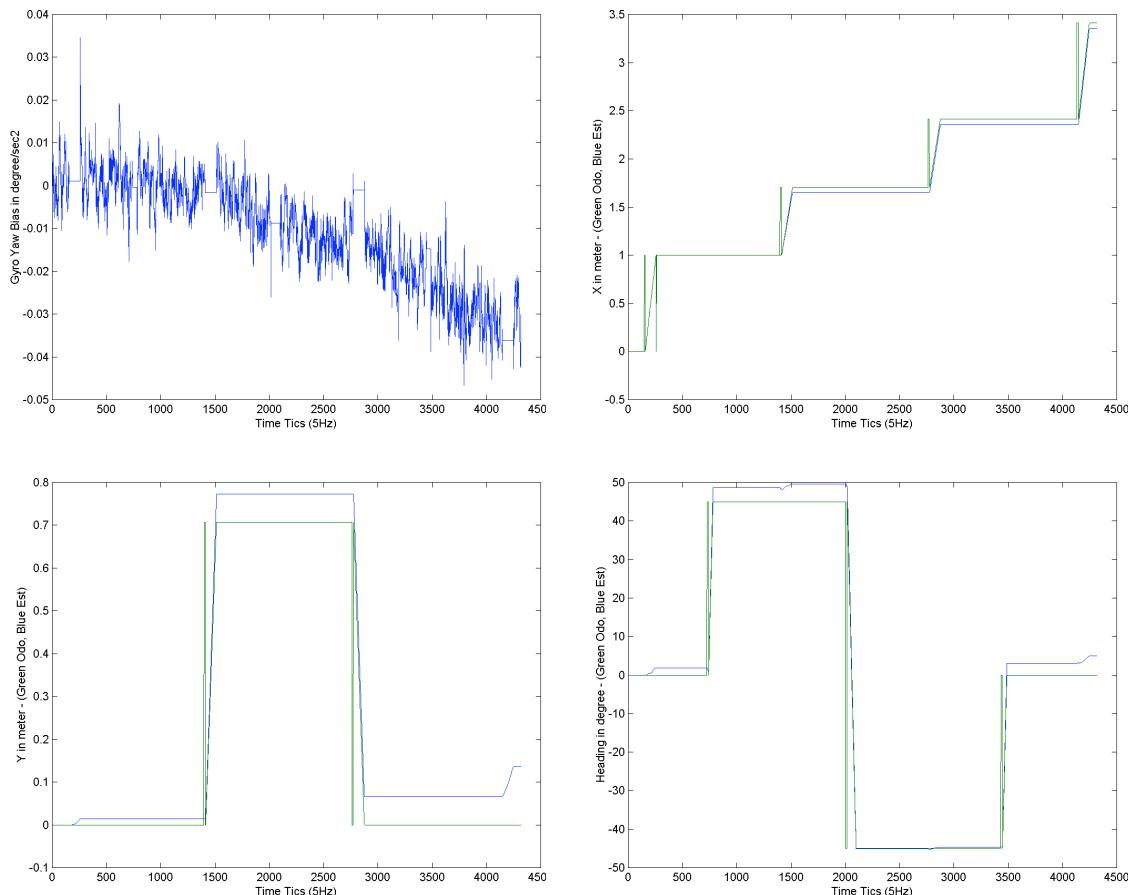


Test5	E1	E2
Move(0,-5)		
Theory		
X	0	0
Y	0	0.02
Heading	-5	0.2775
EKF		
X	0	0
Y	0	0.02
Heading	-4.972	0.028
Odo		0.2495
X	0	0
Y	0	0
Heading	-5	0
Total St.		
X	0	
Y	0.02	
Heading	-4.7225	
Overall Error:	0	0.02 EKF 0.02 Commanded

#### 4-1-6 EKF Sequential Path Drive Tests

This series was designed to test EKF behavior for the types of sequential drive and turn sequences typically seen during obstacle avoidance navigation.

##### Test1: Zig-Zag Drive



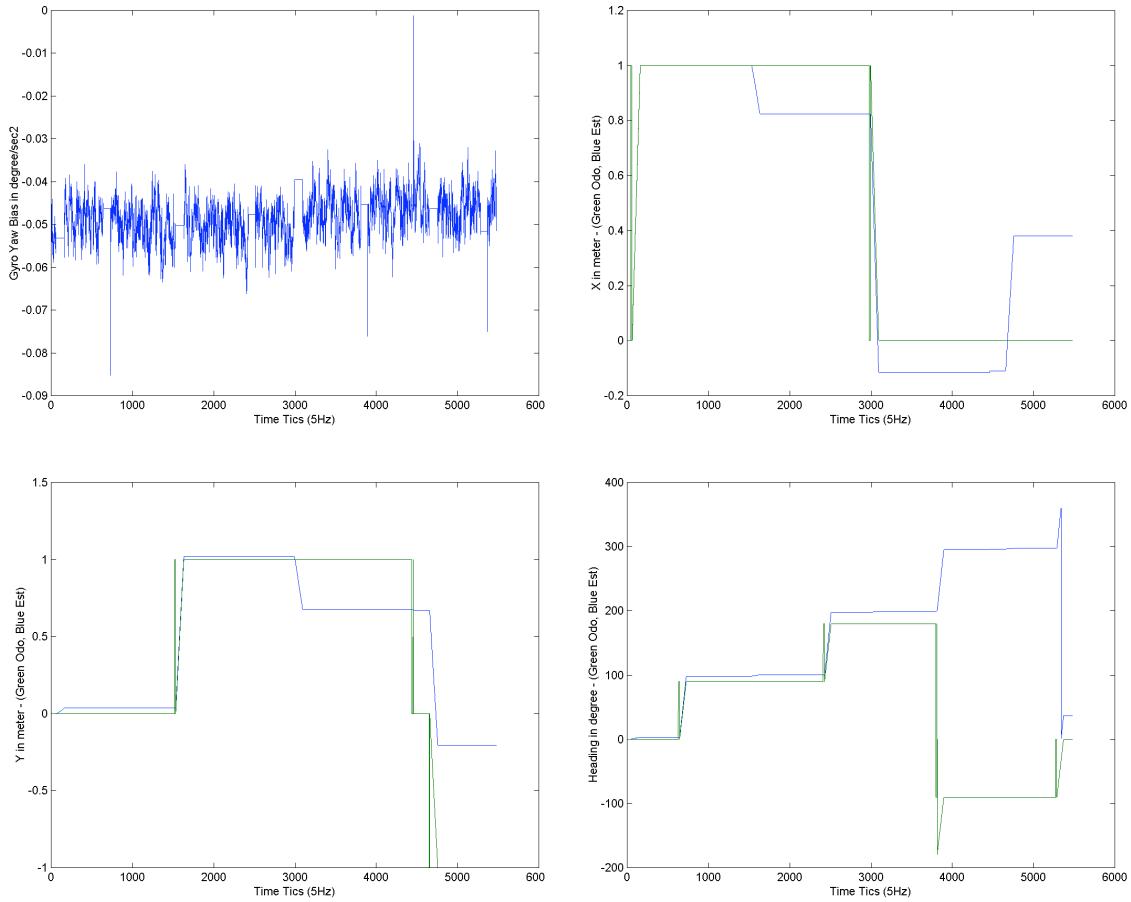
Test1	Move(1,0)		Move(0,45)		Move(1,0)	
	E1	E2	E1	E2	E1	E2
<b>Theory:</b>						
X	1	0.07	1	-1	1.707	0.15
Y	0	0.03	0	0	0.707	-0.08
Heading	0	1.47	45	2.6	45	2.64
<b>EKF</b>						
X	0.9997	-0.08	0.9997	-0	1.6509	-0.1
Y	0.0141	0.01	0.0141	0.01	0.7728	0.07
Heading	1.866	1.87	-0.4	48.654	3.65	-1
<b>Odo</b>						
X	1	0	1	0	1.707	0
Y	0	0	0	0	0.707	0
Heading	0	0	45	0	45	0
<b>Total St:</b>						

## EKF Test Report

---

X	1.0747				1.858			
Y	0.0296				0.624			
Heading	1.474				47.638			
Overall Error:	1.41 7.66				47.638			
		8.04					4.32	12.8
								8.62
	E1	E2	E1	E2	E1	E2	E1	E2
Move(0,-90)	Move(1,0)				Move(0,45)			
1.707	-1.7	2.414	0.339	2.414	-2	3.414	0.16	
0.707	-0.7	0	0.049	0	0	0	0	0.07
-45	-1.7	-45	-1.899	0	0.7	0	1.46	
1.6509	-0.1	-1.7	2.3577	-0.06	0.395	2.357	-0	-2
0.7728	0.07	-0.8	0.0655	0.066	-0.017	0.0655	0.1	-0
-45.0887	-0	-1.6	-44.73	0.27	-2.169	3.092	3.1	-2
1.707	0	2.414	0	2.414	0	3.414	0	
0.707	0	0	0	0	0	0	0	
-45	0	-45	0	0	0	0	0	
	2.7525				3.575			
	0.0488				0.069			
-46.657	-46.8989				0.6521			
	8.637094 2.879 13.17				1.456969			
			11.4				3.725	5.76
								4.38

## Test 2: Square Drive



### Test2

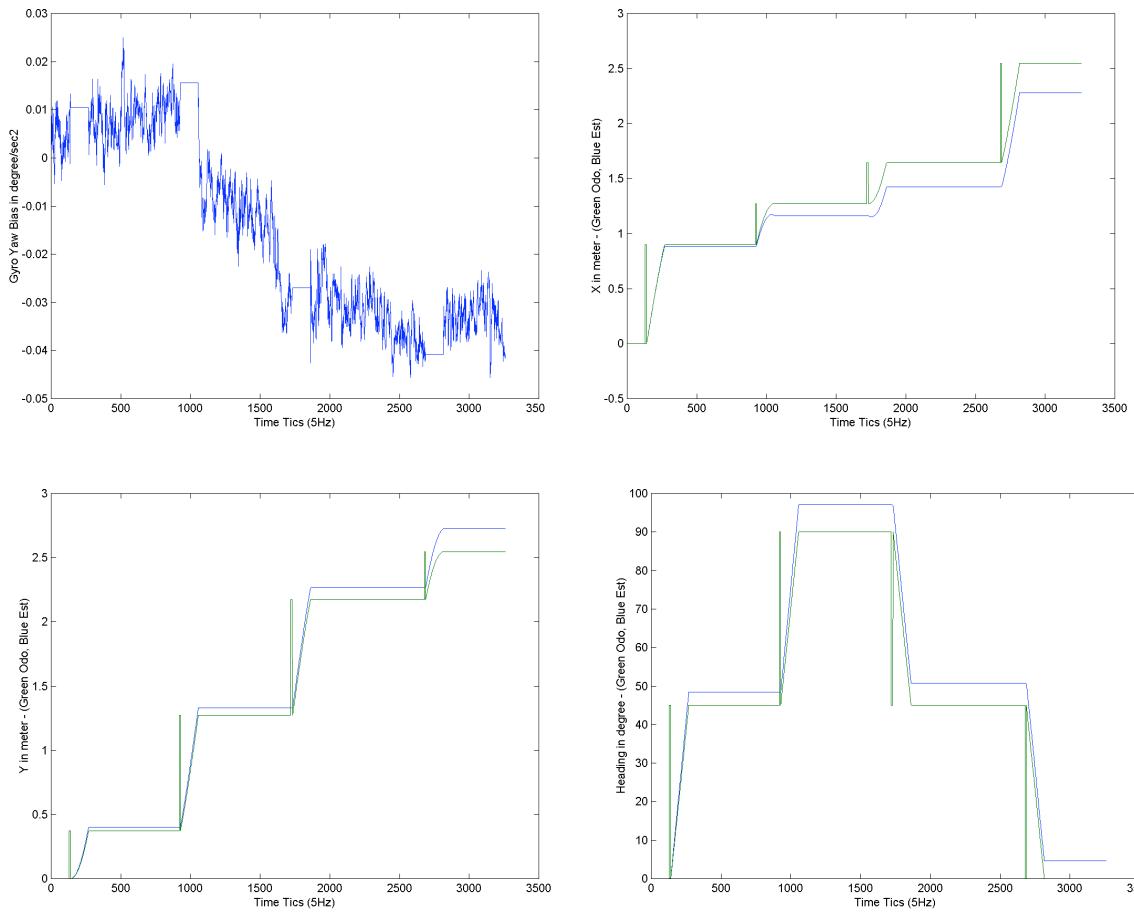
	Move(1,0)		E1		E2		Move(0,90)		E1		E2		Move(1,0)		E1		E2		Move(0,90)		E1		E2	
<b>Theory:</b>																								
X		1		0.081				1		0		1		-0.1		1								
Y		0		0.034				0		0		1		0.08		1								
Heading		0		1.79				90		6.1		90		7.35		180		14.7						
<b>EKF</b>																								
X	0.99923	8E-04	0.081			0.999				0.82343	0.18	0.12	0.823433	0.18										
Y	0.0353	-0.04	-0.966			0.0353				1.01967	-0	0.06	1.019667	-0										
Heading	2.729	-2.73	-0.939			98	-8	-2	100.11	-10	-2.8	197.87921	-18	-3.1										
<b>Odo</b>																								
X	1	0				1	0			1	0			1	0			1	0					
Y	0	0				0	0			1	0			1	0			1	0					
Heading	0	0				90	0	6.1	90	0	7.35		180	0	14.7									
<b>Total St:</b>																								
X		1.0812								0.9461														
Y		0.0337								1.0816														

## EKF Test Report

---

Heading	1.79		96.12		97.35		194.73				
Overall Error:	3.531	8.199			8.88	6.87					
	8.792					4.89					
Move(1,0)	E1	E2	Move(0,90)	E1	E2	Move(1,0)	E1	E2	Move(0,90)	E1	E2
0	-0.1		0		0	0.3		0			
1	-0.2		1		0	-0.18		0			
180	14.7		270		20	270		21.6		0	30
-0.11516	0.02		-0.11516	0.12		0.38014	-0.4	-0.09	0.380146	-0.4	
0.674722	0.13		0.674722	0.33		-0.20432	0.2	0.03	-0.20432	0.2	
198.7328	-4.1		295.0702	-25.1	-5	297.356	-27	-5.78	36.52	-37	-6.7
0	0		0	0		0	0		0	0	
1	0		1	0		-1	-1		-1	-1	
180	0		-180	0	470		-90	0		0	0
-0.0942						0.295					
0.8092						-0.1752					
194.68			289.96			291.58			29.85		
11.5	4.54						10.8	2.25			
	7.09							8.58			

### Test 3: S-Arc Drive



Test3	E1		E2		E1		E2		E1		E2	
Theory:	Move(45,1)		Move(45,1)		Move(-45,1)		Move(-45,1)					
X	0.9007		0.07	1.273		0.2	1.646		0.3	2.546		-0.3
Y	0.3731		0.03	1.273		0	2.173		0.1	2.546		0.52
Heading	45		2.09	90		4.1	45		1.8	0		3.96
EKF												
X	0.8833	-0	0.09	1.1631	-0.11	0.3	1.423	-0.2	0.5	2.28	-0.27	-0
Y	0.4018	0	-0	1.3303	0.057	-0	2.267	0.09	-0	2.72	0.174	0.35
Heading	48.4647	3.5	-1.4	97.08	7.08	-3	50.81	5.8	-4	4.59	4.59	-0.6
Odo												
X	0.9002		0	1.273		0	1.646		0	2.546		0
Y	0.3728		0	1.273		0	2.173		0	2.546		0
Heading	45		0	90		0	45		0	0		0

## **EKF Test Report**

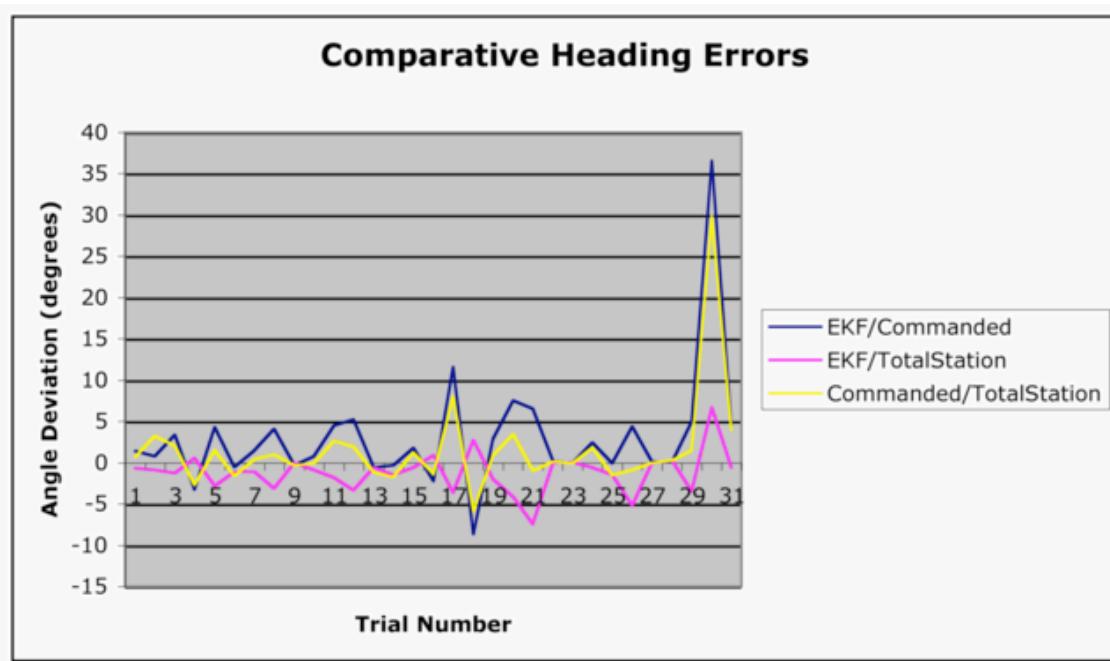
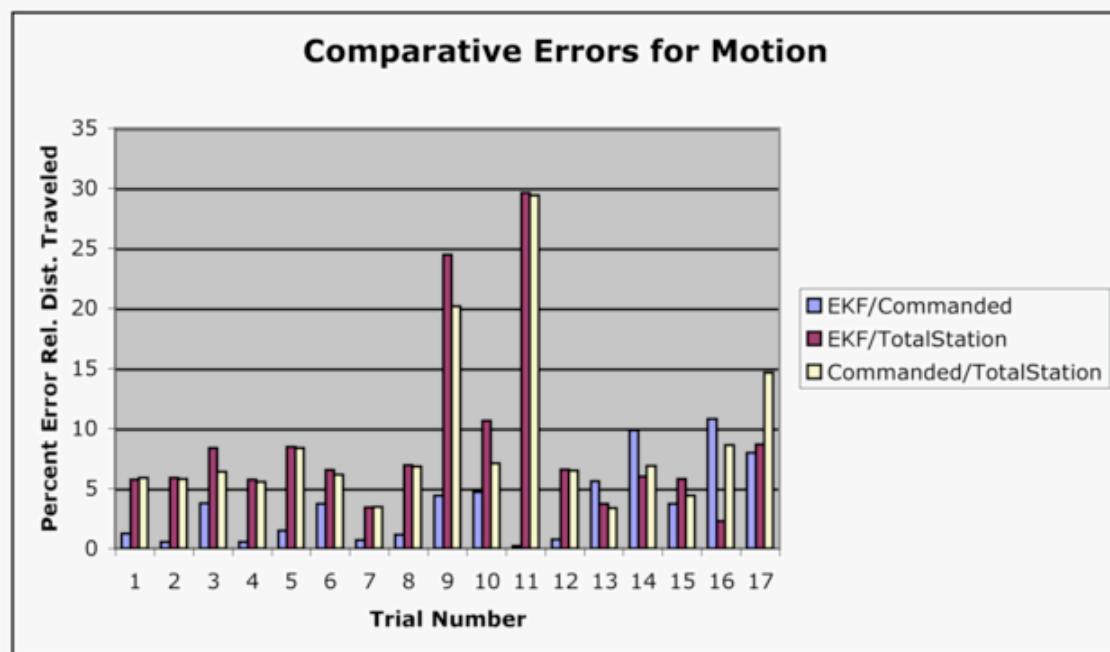
---

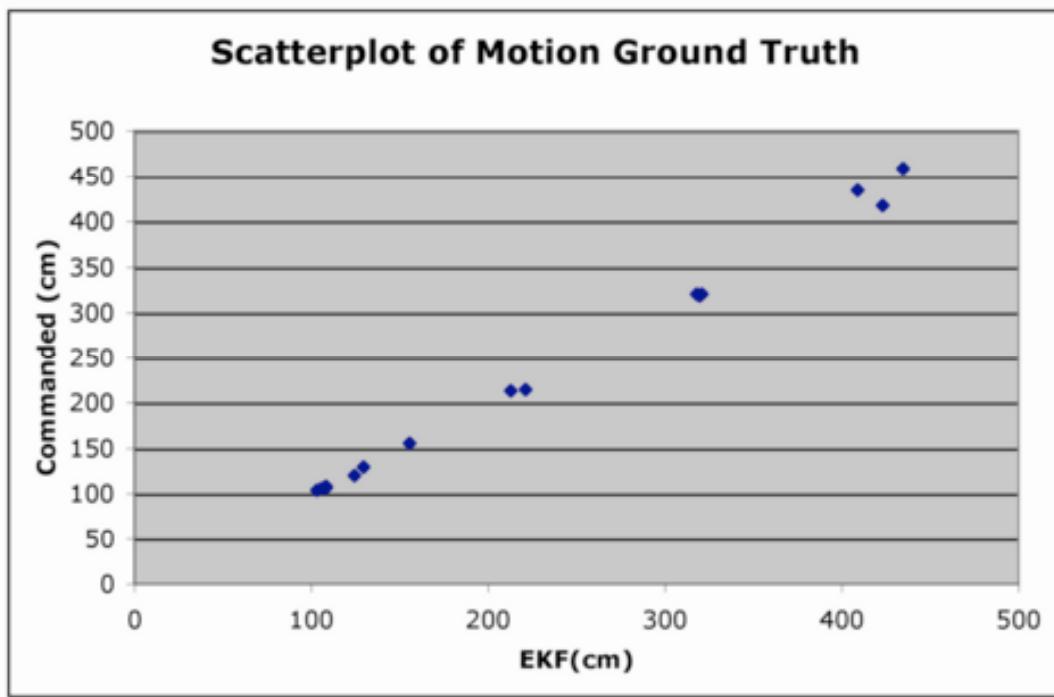
Total St:

X	0.97	1.431	1.927	2.2769
Y	0.401	1.307	2.233	3.0659
Heading	47.09	94.05	46.82	3.96

Overall Error:	3.4 8.67	6.197 13	8.07 17	7.946 8.65
	7.47	8.1	9.6	14.6

## Summary Charts





The first plot shows the comparative errors for the driving tests in terms of the EKF vs Commanded, the EKF vs Ground Truth, and the Commanded vs. Ground Truth. Tests 9 and 11 correspond to the Drive Arcs (1m, 45°) and (1 m, -45°) which were also done during Tests 3 and 4. They were treated as outliers since the results could not be replicated during subsequent testing.

The second plot shows the comparative heading errors in degrees in terms of the EKF vs Commanded, the EKF vs Ground Truth, and the Commanded vs. Ground Truth. Test 30 corresponds to the Square Drive (Square with 1 m sides) and the average heading error for each turn-in-place at the corners is 8.69%, which is a significant deviation from the average heading error of 2.83% for a single turn-in-place. This may be an implementation issue and can only be resolved through further testing.

The final plot shows the comparative error of Commanded vs EKF with respect to the Ground Truth. The plot is linear, which indicates that there is a constant error with respect to the distance traveled, the majority of which can be traced to an inaccurate effective wheel diameter. This issue is at the heart of odometry errors and will need to be resolved through other means such as visual odometry.